Callide Unit C4 turbine generator failure – 25 May 2021

Technical investigation summary

13 February 2024

Contents

Disclaimer

This report is a technical investigation summary and is to provide key stakeholders with an overview of the Unit C4 incident that occurred on 25 May 2021, the technical contributing factors and actions undertaken since the event.

Abbreviations

Abbreviation	Term
AC	Alternating current
ACS	Automatic Changeover Switch
Amp	Ampere
Bd	Board
DC	Direct current
EDG	Emergency diesel generator
GCB	Generator circuit breaker
HP	High pressure
IP	Intermediate pressure
kV	Kilovolt
LP	Low pressure
ms	Millisecond
rpm	Revolutions per minute
V	Volt

Purpose

On 25 May 2021, an incident occurred on Unit C4 at Callide Power Station that caused extensive damage and impacted the transmission network[1].

No personal injuries were sustained during the event.

Figure 1: Unit C4 – post-event photograph

Post-event damage assessment identified the following:

- Considerable damage to the high pressure (HP), intermediate pressure (IP) and low pressure (LP) turbines including multiple shaft failures. Complete replacement was required.
- Considerable damage to the generator stator, rotor and exciter. Complete replacement was required.
- Insulation failure of the generator transformer and 275 kilovolts (kV) landing structure. Complete replacement was required.
- Impact damage to the condenser.
- Impact damage from debris to the turbine hall structure and the adjacent unit (C3).

Damage to Unit C4 was principally contained to the turbine floor with minimal impact to the boiler and turbine auxiliary equipment.

This report provides an overview of the incident, the technical contributing factors, and actions undertaken since the event.

Callide C Power Station overview

Callide Power Station is located near Biloela, Queensland, and is comprised of two power plants: Callide B and C, each with two generating units (B1 and B2; C3 and C4). All four units are operated from a common control room.

Electricity is generated at Callide C by grinding coal to a fine powder and burning it in a boiler. The fire in the boiler heats water, converting it to steam at very high temperatures that is piped to the turbine. The steam rotates the turbine at 3,000 revolutions per minute (rpm), which drives a generator that converts the mechanical energy into electricity.

The generated electricity is stepped up to transmission voltage (275 kV) by a transformer and is exported to the Calvale Substation (located approximately one kilometre from Callide C). The substation is operated by Powerlink Queensland and is part of the Queensland power grid infrastructure.

[1] For an analysis of what happened on the transmission network following the Unit C4 incident, refer to AEMO (Australian Energy Market Operator) (2021) *Final Report – Trip of multiple generators and lines in Central Queensland and associated under-frequency load shedding on 25 May 2021* [PDF, 10.53 MB] AEMO, accessed 1 February 2024.

Key systems relevant to the incident

The electrical distribution system of a coal-fired power station consists of two major electrical systems – the alternating current (AC) system, and the direct current (DC) system.

The AC system is taken from the generator output and powers most of the unit auxiliaries required for power generation.

The DC system is a battery-backed, high reliability system that provides power to critical control and protection systems. It also provides emergency backup to critical systems such as turbine lubrication oil and generator sealing oil.

The DC system (including battery back-up) powers the unit control, monitoring, and unit protection systems required for the safe operation of Unit C4.

The DC system is powered by a combination of a battery charger and backup battery. The backup battery is critical to the reliability of the DC system, as it enables the DC system to remain energised in the event of a charger failure or AC power interruption.

Callide C includes three DC systems – Unit C3, Unit C4 and 'Station'. The Station DC primarily provides redundancy to both units.

All three DC systems include independent battery chargers and batteries (220V DC).

Unit protection systems monitor critical parameters of the unit and remove it from service (trip) if the safe operating envelope is exceeded.

The turbine lubrication system provides lubrication oil to the turbine and generator bearings, allowing the rotor to rotate with minimal friction. This system has redundancy and includes two AC pumps and an emergency DC pump.

The generator sealing oil system creates an oil pressure seal preventing the hydrogen gas, which cools the generator, from escaping. This system has redundancy which includes an AC pump and an emergency DC pump.

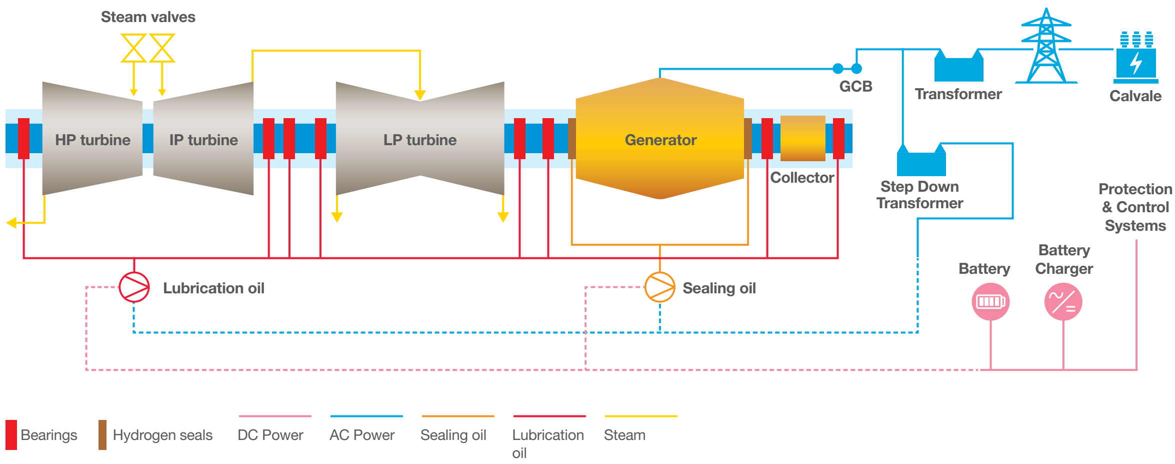


Figure 2: Callide C turbine generator overview

Background

In the 18 months leading up to the Unit C4 incident, an upgrade program had been initiated to replace the battery chargers on Unit C3, Station, and Unit C4.

The Unit C3 and Station battery chargers were replaced and successfully brought back into service.

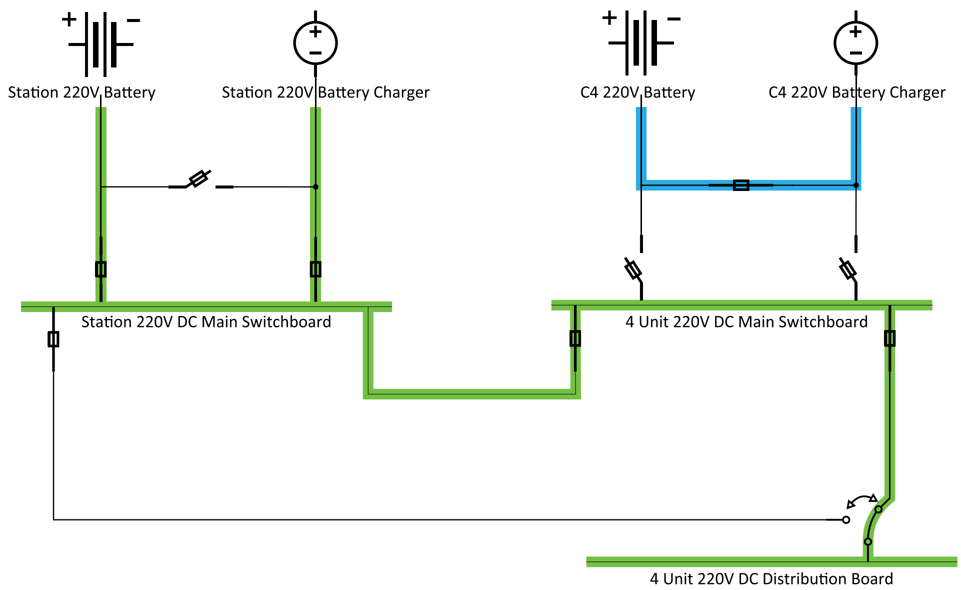
By May 2021, the Unit C4 battery and battery charger had been disconnected from the system and the battery charger had been replaced.

During this time, the Unit C4 DC system was configured to receive power from Station, via a switch, called a Station Interconnector.

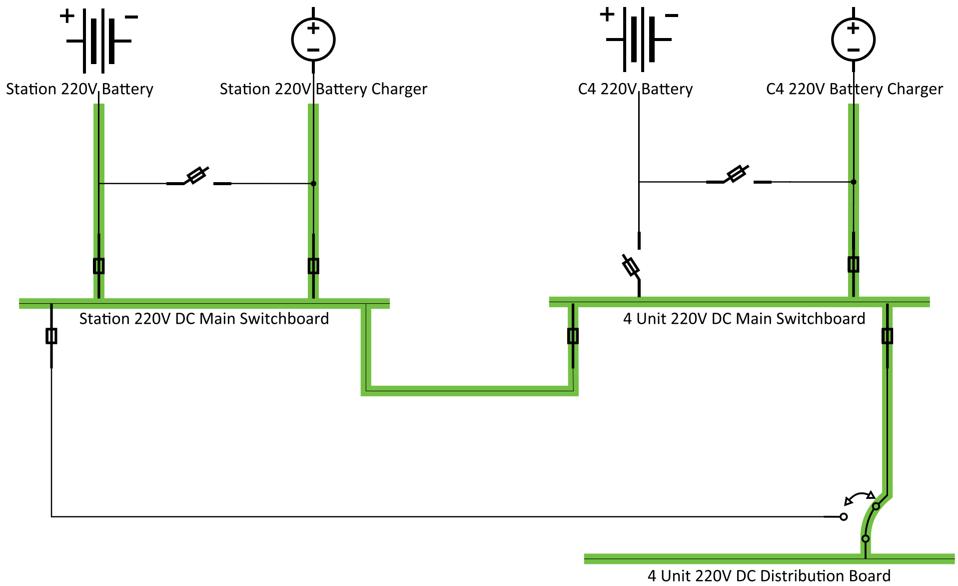
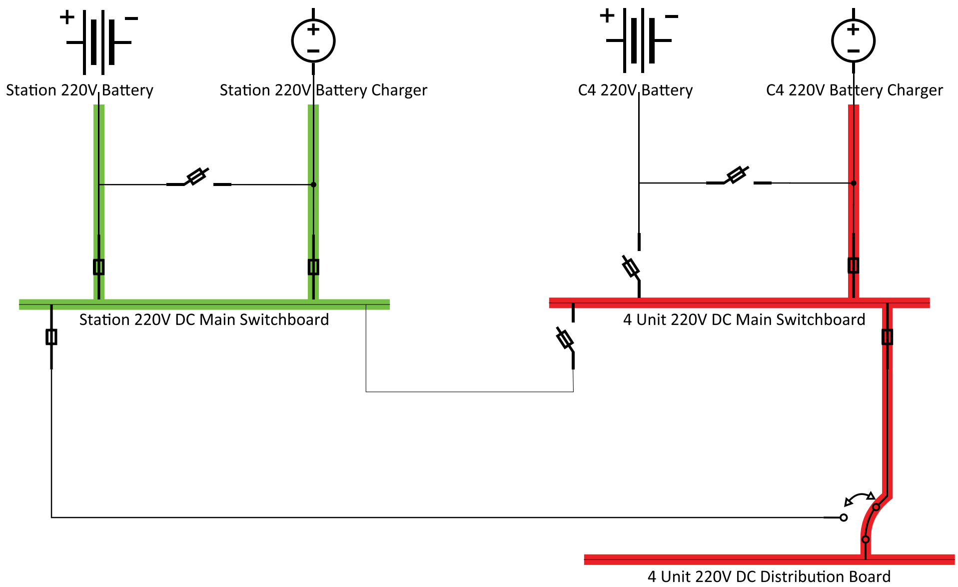
The Unit C4 incident occurred during the re-connection of the new Unit C4 220V battery charger.

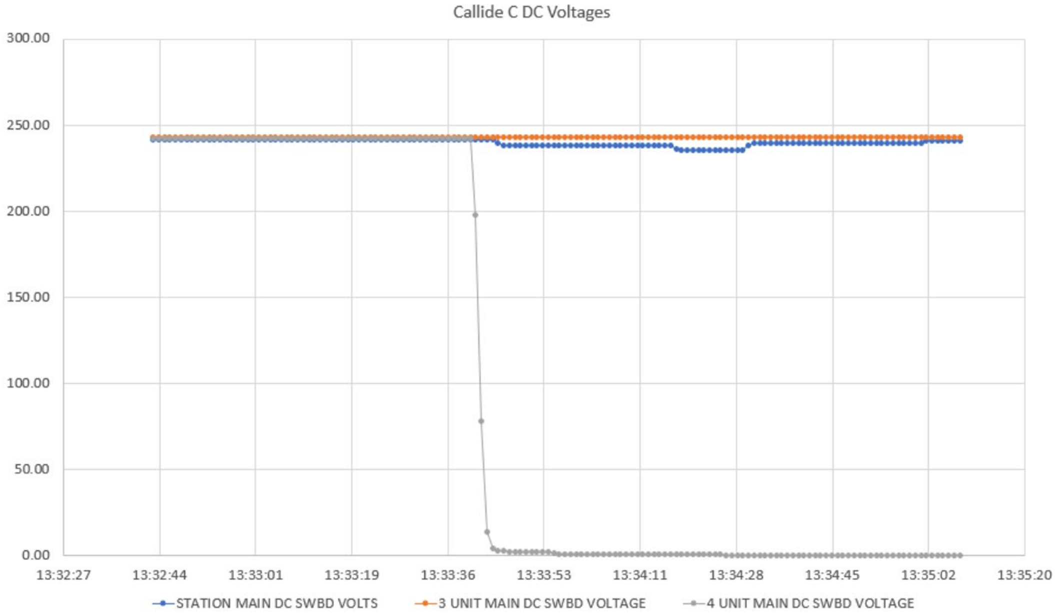
Timeline

The timeline for the Unit C4 incident is below:

Time	Event
	24 May 2021
14:08	C4[1] 220V battery charger energised and returned to service in offline charging mode (connected to C4 battery only). Offline charging is required to ensure that the battery is fully charged prior to being returned to service.  **Figure 3: DC configuration 24/05/2021 14:08. Colours denote different circuits.**
20:00	C4 220V battery was successfully charged and maintained in a fully charged state.

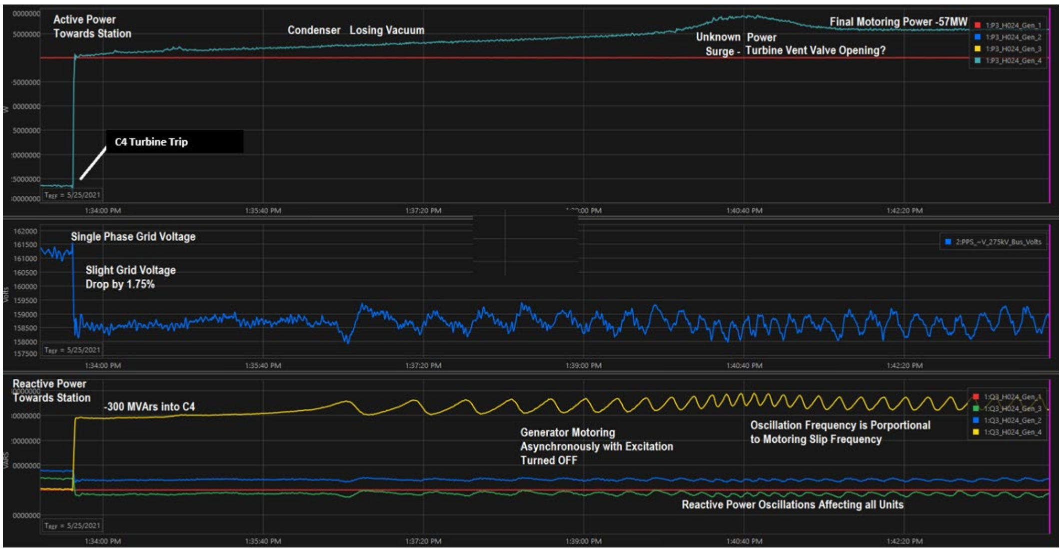
[1] Unit C4 referred to as 'C4' for brevity in table.

Time	Event
	25 May 2021
13:28	Switching commenced to return C4 battery charger to service into its typical configuration.
13:32	C4 offline battery charger circuit was opened and C4 220V battery charger was connected to Unit C4 220V DC Main Switchboard. Configuration as per Figure 4.  **Figure 4: DC configuration 25/05/2021 13:32.**
13:33	Unit C4 to Station Interconnector opened (initiating event), Unit C4 220V DC voltage decayed to zero volts.  **Figure 5: DC configuration 25/05/2021 13:34. Colours denote different circuits.**

Time	Event
13:33	Callide C DC voltage data is shown in Figure 6.  **Figure 6: DC voltage data**

13:33 – 13:34	The decaying DC voltage on C4 triggered several events.
	• Turbine trip (closure of steam supply valves)
	• Excitation system trip
	• Failure of generator protection systems (X and Y, GCB)
	• Loss of 6.6kV and 415 auxiliary AC power supplies. This failure also initiated:
	    ○ Loss of turbine lubrication oil supply due to both AC and DC pumps having no power supply
	    ○ Loss of generator sealing oil supply due to both AC and DC pumps having no power supply
	    ○ Loss of control room screens
	    ○ Boiler tripping due to loss of major drives (fans, mills etc.) following the loss of 6.6kV supplies.

13:34	The emergency diesel generator (EDG) detected an undervoltage on the Station emergency 415V switchboard. The EDG started in automatic mode and energised the Station 415V emergency board in 25 seconds. The automatic switching sequence did not operate to energise the C4 415V emergency board, and the C4 415V emergency board remained de-energised. The automatic switching sequence required 415V AC circuit breakers to operate in order to energise essential equipment only. These are controlled by 220V DC and, as this supply was unavailable, this did not occur.

Time	Event
13:34 – 14:05	The turbine tripped (closure of steam supply valves) due to the loss of AC and DC supplies to the governing oil system and resulted in the turbine/generator transitioning from generating power to absorbing power from the grid. This is called 'motoring'. Motoring of a generator occurs when the generator is being driven by the system it is connected to, rather than driving the system itself. This can happen when the generator is not producing power but is instead consuming power from the system, which can lead to mechanical stress and potential damage to the generator. The generator was actively absorbing power from the grid, operating as an asynchronous motor, without any cooling systems functioning. The generator protection system has reverse power protection to disconnect the unit from the grid in this situation. However, due to the lack of DC power supply this protection was not able to operate. The turbine/generator was motoring at ~3,000 rpm without bearing lubrication due to the loss of both AC and DC power supplies. This generated excessive heat, melting the bearings and damaging the shaft, which resulted in shaft failures in several locations. The loss of AC and DC power supplies resulted in the loss of sealing oil supply and the release of hydrogen through the shaft seals resulting in an explosive mixture, which is likely to have been ignited by the elevated temperatures on the shaft, resulting in rapid hydrogen combustion/explosions.
14:06	The incident ceased when the generator suffered a significant electrical fault, the magnitude of which resulted in considerable damage to the generator transformer and in the de-energisation of the Calvale substation. The motoring ceased, the turbine generator stopped rotating and the incident reached its conclusion.  Figure 7: Electrical trends – motoring event

Technical discussion

220V DC system design

Callide C was designed to include three independent 220V DC systems, one for each unit and one for Station, that provides redundancy for the unit batteries.

The design also includes a key interlock system which controls the sequence and plant configuration during switching operations.

The original design of this key interlocking system was intended to prevent two batteries from being connected in parallel.

At the time of the Unit C4 incident, this interlock prevented the Unit C4 220V battery from being connected until the Station Interconnector was opened. This resulted in a circuit configuration as shown in Figure 8.

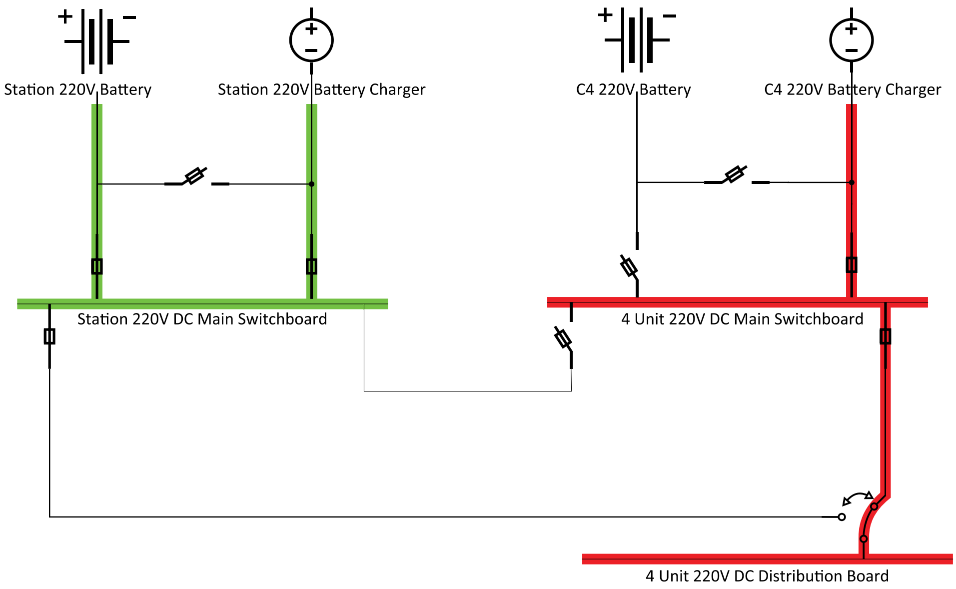


Figure 8: DC configuration 25/05/2021 13:34. Colours denote different circuits.

Therefore, following the opening of the Station Interconnector, Unit C4 220V DC Main Switchboard's sole source of supply was the Unit C4 220V battery charger.

In this configuration the reliability of the supply to the Unit C4 220V DC Main Switchboard is reduced to the reliability of the AC system powering the Unit C4 battery charger.

Other power station DC system designs (e.g. Callide B), allow paralleling of batteries, which provides greater reliability during switching. This was not the case for Callide C Power Station.

Automatic Changeover Switch

Critical functions such as generator protection and associated generator circuit breaker (GCB) have two independent systems to increase reliability. The generator protection consists of an 'X' and 'Y' system, each operates independently with its own power supply to protect the generator.

In the Callide C design, one supply ('X') is from the Unit 220V DC Main Switchboard and the other ('Y') is from the Unit 220V DC Distribution Board.

The Unit 220V DC Distribution Board has two supply sources, controlled by an Automatic Changeover Switch (ACS), one from the Unit 220V DC Main Switchboard and the other from the Station 220V DC Main Switchboard. The ACS was configured with the preferred supply being the Unit 220V DC Main Switchboard.

This ACS is a 'break-before-make' switch which is designed to transfer automatically to the standby supply upon loss of the preferred supply.

This loss of supply from the Unit 220V DC Main Switchboard should have initiated the ACS to transfer supply to the Station 220V DC Main Switchboard. In this instance the ACS did not do so, which meant the 'Y' Generator Protection system was not energised and this system could not operate the GCB.

The ACS did not operate automatically as it was damaged during a dual unit trip event in January 2021. Following the January event, CS Energy undertook an engineering investigation and worked with AEMO to return the units to full capacity. The actions identified during the investigation included a modification to the ACS control circuit. At the time of the Unit C4 incident the modification was not yet ready for implementation, but was within the planned timeframe for the modification.

On the day of the incident, the ACS was available for manual operation but was not operated. Systems to understand the incident were unavailable in the control room and switching personnel exited the switchroom as part of the site evacuation to manage personal safety.

However, even if the ACS had operated, it would not have resulted in supply to the emergency turbine lubrication oil or the emergency sealing oil pump and therefore it is unlikely that it would have prevented the turbine bearing damage or rapid hydrogen combustion/explosion.

Had the 'Y' generator system been energised following the operation of the 'break-before-make' switch, it would be expected that reverse power protection would have tripped the GCB and it is likely that the generator would have ceased motoring within a matter of seconds.

The 'X' generator protection system was unable to operate as the Unit C4 220V Main Switchboard was de-energised.

Operation of battery chargers in parallel

Despite successfully charging the Unit C4 battery on the day prior to the incident, the Unit C4 220V battery charger failed to maintain the voltage on the Unit C4 220V DC Main Switchboard following the opening of the Station Interconnector.

The 220V DC battery chargers do not share load when operating in parallel. Instead, they operate independently. This means that the charger with the highest output voltage will take all the load, while the other outputs no current.

Despite the Unit C4 battery charger being set to a higher voltage than the Station battery, the actual Station and Unit C4 battery charger currents immediately prior to the opening of the Station Interconnector were as shown in Figure 9.

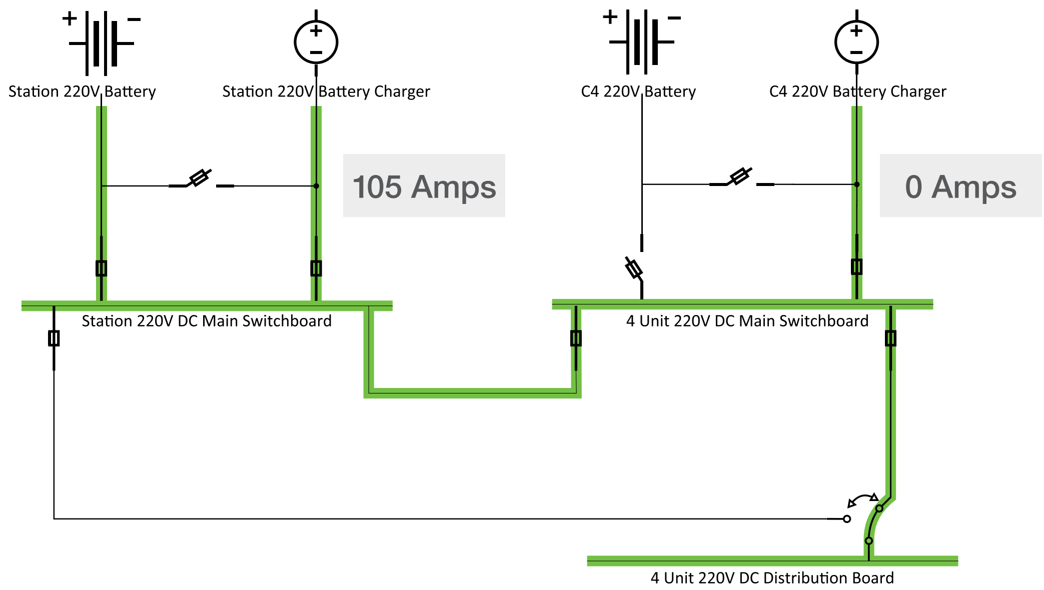


Figure 9: Battery charger current when operating in parallel – 25 May 2021 13:32

The Station 220V battery charger was providing all the load. On opening the Station Interconnector the Unit C4 220V battery charger had to detect the voltage drop and raise output to maintain the voltage. The Unit C4 220V battery charger failed to respond quickly enough to maintain the DC voltage before the loss of the AC supply. Once the AC supply was lost the Unit C4 220V battery charger had no opportunity to recover the voltage.

Loss of AC on loss of DC

Within two seconds of the Station interconnector being opened, there was a loss of all 6.6kV and 415V AC supplies to Callide Unit C4.

This loss of AC supply was significant because:

- It prevented the Unit C4 220V battery charger from recovering due to loss of supply
- The loss of the two main turbine lubrication oil pumps resulted in a loss of lubrication while the generator was motoring, causing shaft heating and subsequent damage
- The loss of main sealing oil pumps resulted in a loss of hydrogen seals, release of hydrogen and ignition.

The loss of AC supply was a result of the 6.6kV incomer circuit breakers tripping. Protection relay alarm logs and subsequent testing have confirmed that the trip function was the 'arc flap' protection.

The 'arc flap' protection normally operates in this way: if an internal failure were to happen within the switchgear, an electrical arc would develop. This will cause a build-up of pressure within the switchgear which will be vented through the arc flaps. A switch is located on each of these flaps, and upon opening of the flap (to relieve the pressure) the protection relay trips the circuit breaker to de-energise the fault.

These switches are wired as 'normally closed' contacts, which open in the event of a fault.

The loss of DC will simulate a 'normally closed' contact opening and initiate a trip.

The arc flap protection parameters of the 6.6kV protection system are as follows:

Arc flap protection trip initiation voltage	<164V DC
Protection relay minimum operating voltage	>60V DC
6.6kV circuit breaker minimum trip voltage	>101V
Protection relay processing time	~5 ms
6.6kV circuit breaker opening time	~8 ms

Figure 10 plots the DC voltage decay during the incident against the arc flap protection parameters. In this case, the manner in which the DC voltage decayed (gradually rather than immediately) was such that there was sufficient time and voltage for the protection relay to trip the 6.6kV circuit breaker.

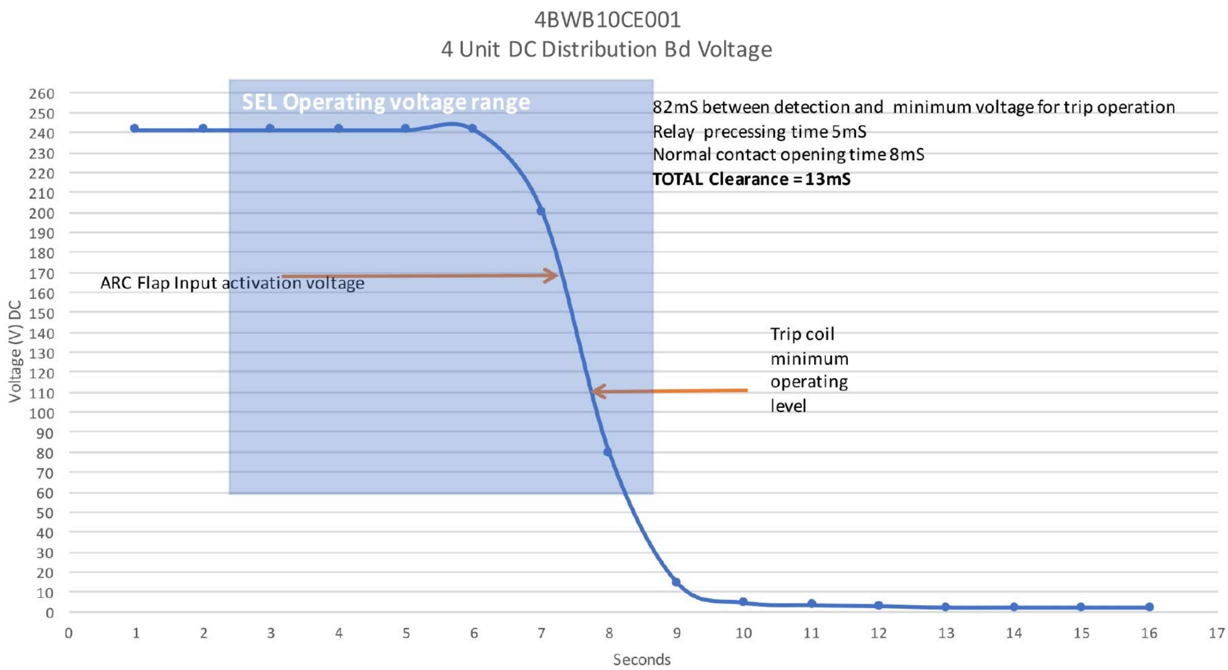


Figure 10: Unit C4 incident DC decay and arc flap activation

6.6kV configuration

At Callide C this system does not include a dedicated Station Transformer for supplying station loads, as is the case for other Australian power station units (e.g. Callide B). Instead, it relies upon the Unit supplies.

The Unit 6.6kV Boards are connected to the station boards, and can be supplied from either Unit 3, Unit 4 or it can be shared.

At the time of the Unit C4 incident, all station supplies were supplied from Unit C4, therefore the loss of C4 AC supplies also caused a loss of Station AC supplies.

Emergency diesel generator

An emergency diesel generator (EDG) is installed at Callide C. It is designed to automatically start upon loss of voltage on the Station Emergency 415V Switchboard.

Once the EDG starts and 415V is re-established on the Station Emergency 415V Switchboard, automatic switching sequences are installed to energise the C3 Emergency 415V Switchboard and the C4 Emergency 415V Switchboard. This sequence ensures critical supplies such as battery chargers are maintained.

During the incident, the EDG automatically started and energised the Station Emergency 415V Switchboard within 25 seconds, however the C4 Emergency 415V Switchboard was not able to be energised as C4 220V DC supply was lost, preventing automatic operation of the required circuit breakers.

During the incident, the Station 220V DC system remained energised enabling the EDG to start and energise the Station Emergency 415V Switchboard.

Fault tree

A fault tree has been developed for the Unit C4 incident defined as 'Turbine generator failure after motoring for 33 minutes without lubrication oil'. A fault tree is a diagram representing the hierarchy of contributing factors and their interrelationships. The relationships between contributory factors are described utilising logic 'gates', typically:

AND – All inputs must be true to get a true output.

OR – Any input must be true to get a true output.

The fault tree shows that the turbine generator failure required the failure of the entire turbine lubrication system and back-up systems:

- failure of the 'A' AC lubrication oil pump (due to loss of AC from unintended tripping of arc flash protection)
- failure of the 'B' AC lubrication oil pump (due to loss of AC from unintended tripping of arc flash protection)
- failure of the DC lubrication oil pump (due to loss of DC from the loss of battery charger supply and no battery supply due to interlocking)

The loss of lubrication caused extreme overheating of bearings leading to mechanical failure.

AND

The generator protection systems failed to disconnect the generator from the grid during the motoring event due to:

- failure of 'X' generator protection (due to loss of DC from the loss of battery charger supply and no battery supply due to interlocking)
- failure of 'Y' generator protection (loss of DC from the battery charger supply and no battery supply due to interlocking co-incident with the loss of the automatic backup functionality of the Auto Changeover Switch)

These protection systems did not detect the motoring and de-energise the generator in a timely manner to prevent damage.

The loss of the DC system was initiated when the station interconnector was opened and the C4 220V battery charger failed to maintain the voltage on the C4 Unit Main Switchboard that was also supplying the C4 Unit 220V Distribution Board.

The interlocking design prevented a battery from being connected during this operation.

This loss of DC initiated a loss of AC supply due to arc flap protection, which prevented the C4 220V Battery charger from recovering the DC voltage.

The ACS was one of a number of barriers which did not prevent this incident from occuring.

The unavailability of the automatic function of the backup ACS to operate prevented the recovery of the DC supply to the Y Generator Protection system. However, even if the ACS had operated, it would not have resulted in supply to the emergency turbine lubrication oil or the emergency sealing oil pump and therefore it is unlikely that it would have prevented the turbine bearing damage or rapid hydrogen combustion/explosion.

LEGEND

AND – All inputs must be true to get a true output

OR – Any input must be true to get a true output

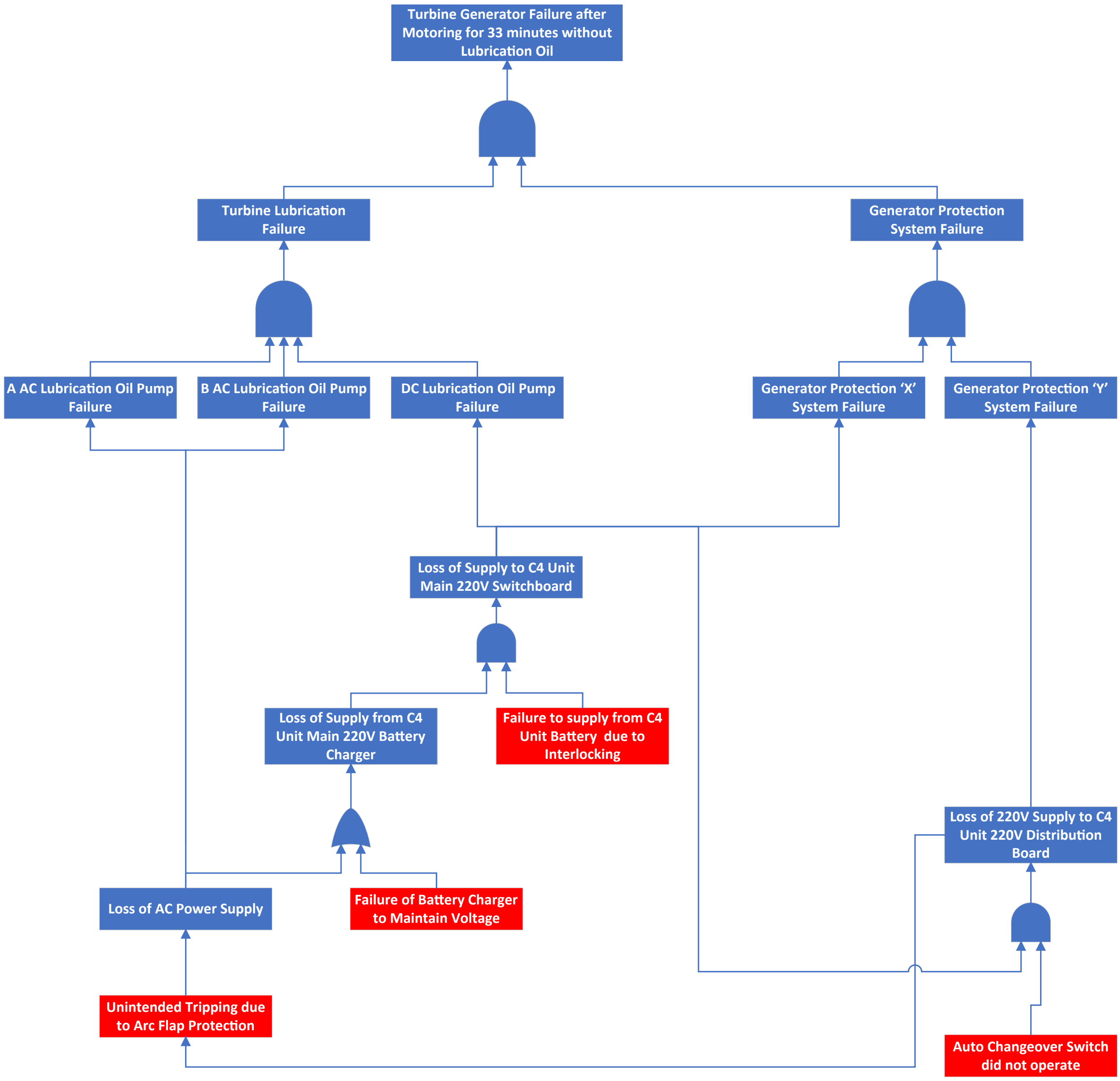


Figure 11: Unit C4 event simplified fault tree

Contributing factors

The significant contributors to the Unit C4 incident (identified in red in Figure 11) have been identified, and are summarised below in order of importance:

1) **Interlocking design preventing battery being connected during switching operation**

   The interlocking design prevents two batteries being connected in parallel during switching operations, therefore limiting the reliability of the critical DC supply system to that of the AC supply system.

   Had a charged battery been able to be connected through all switching operations, the incident would likely have been prevented.

2) **Unintended tripping due to arc flap protection**

   Loss of the AC supply due to arc flap protection on loss of DC supply was not an expected occurrence and is not the intent of the protection design. This resulted in the loss of turbine oil pumps and prevented the battery charger recovering the DC voltage.

   Had the AC supply remained in service, the turbine oil and sealing oil pumps would have remained in service and it is likely that the Unit C4 220V battery charger would have recovered the 220V DC, enabling the unit to trip on reverse power in a matter of seconds.

   Arc flap protection should only operate when the arc flaps operate and should be able to ride through short term deviations in DC supply voltage.

3) **Automatic Changeover Switch did not operate**

   The Automatic Changeover Switch did not automatically change over to the available Station Main 220V Switchboard upon the loss of the Unit C4 Main Switchboard supply. This prevented the 'Y' Protection system from tripping the generator and likely ending the generator motoring.

4) **Failure of battery charger to maintain voltage**

   Upon opening of the Station Interconnector, the battery charger did not instantly maintain the DC voltage within the required operating range.

   Ensuring a battery is always connected reduces the criticality of the battery charger response time and is the preferred method to address this.

Improvement actions

The following actions have been taken following the Unit C4 incident:

1) **220V DC main switchboard key interlock modifications**

   The key interlocking circuits have been modified to enable batteries to be paralleled but not battery chargers. This will ensure that during switching operations a battery can always be connected to provide necessary redundancy for critical protection circuits.

   This modification has been applied to Unit C3 and Station 220V Main Switchboard. The modification will be made to Unit C4 prior to its return to service.

   This action addressed Contributory Factor 1 and Contributory Factor 4.

2) **6.6kV unit and Station switchboard arc flap protection modification**

   The arc flap protection logic has been modified with electrical current conditioning such that it will only trip if the arc flap switch operates in association with a high electrical current. This will ensure the arc flap protection will be resilient to short term deviations in DC supply.

   This modification has been applied to Unit C3, Unit C4 and Station 220V Main Switchboard.

   This action addressed Contributory Factor 2.

3) **Automatic Changeover Switch – Preferred position and reliability modifications**

   Additional reliability can be achieved by altering the preferred supply position. This would result in the 'X' protection and the 'Y' protection systems being supplied from different batteries preventing a single point of failure impacting both 'X' and 'Y' protection systems.

   The Automatic Changeover Switch has been modified in two ways:

   1. The preferred position has altered from the Unit Main Switchboard to Station Main Switchboard, this will ensure that 'X' and 'Y' Protection systems are supplied from different batteries, reducing the impact of a single failure.
   2. The control circuitry of the Automatic Changeover has been modified to ensure reliability.

   This modification has been applied to Unit C3 and Station 220V Main Switchboard. The modification will be made to Unit C4 prior to its return to service.

   This action addressed Contributory Factor 3.

4) **Battery charger replacement**

   The Unit C4 220V battery charger installed at the time of the incident includes a single rectifier circuit and as such any reliability issues may cause the unit to cease operating completely. The Unit C3 and Station chargers have been replaced with units with multiple rectifier circuits that include N+3 redundancy and enable online replacement of faulty components. The Unit C4 charger will be replaced with an improved unit prior to its return to service.

   N+3 redundancy means that the three rectifier modules can fail without preventing the charger from providing rated load.

   This action addressed Contributory Factor 4.

5) **Increased redundancy**

   An engineering review has identified that access for maintenance on the three battery systems cannot be completed while maintaining sufficient DC Supply redundancy for online generating units. A project is underway to convert the three battery system into a four battery system, including the installation of an additional switchboard, battery and battery charger.

   This modification will be completed prior to the return to service of C4.

Further information

To view the accompanying animation for this report, visit: www.csenergy.com.au/what-we-do/thermal-generation/c4recovery

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