Technical and Organisational Investigation of the Callide Unit C4 Incident

Month Year

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Executive Summary

EXECUTIVE SUMMARY

The Incident

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1 INTRODUCTION TO THE INVESTIGATION

1.1 Incident

Between 1:33 pm and 2:07 pm on 25 May 2021, Unit C4 at Callide C power station suffered a catastrophic failure. There were no fatalities, but the incident destroyed the turbine and generator of Unit C4 and had a major impact on the Queensland power grid.

1.2 Engagement

On 1 June 2021, Dr Sean Brady of Brady Heywood was engaged by the law firm Norton Rose Fulbright on behalf of CS Energy Ltd, the operator of Callide C power station. This engagement was to conduct an independent investigation into the causes of the incident for the purpose of enabling Norton Rose Fulbright to provide legal advice to CS Energy. Dr Brady's engagement was on a confidential basis and is subject to legal professional privilege.

1.3 Brady Heywood Investigation

Dr Brady assembled a multidisciplinary team to conduct the investigation in two parts, technical and organisational. He supervised the work conducted by the team, and the opinions expressed in this report are his own.

The investigation involved the collection and examination of physical evidence, testing, data analysis, interviews, and a review of CS Energy's records, systems and processes.

1.4 Report

The main body of the report is written for a non-technically trained reader. It is divided into two parts. The technical causes of the incident are discussed in Part A: Technical Investigation. The organisational factors that contributed to the incident hare discussed in Part B: Organisational Investigation.

Further technical discussion is provided in appendices, which are intended for a technically trained reader. There are no organisational investigation appendices.

Documents are cross referenced to the document database provided by Norton Rose Fulbright for the purpose of the investigation.

Names of individuals and other personal identifiers have been de-identified or redacted in the text and images of the report.

1.5 Animation

An animation has been created to aid understanding of this report's technical findings, but it is not intended to replace the report. It has been provided to Norton Rose Fulbright.

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Brady Heywood.

Part A: Technical Investigation

2 OVERVIEW OF PART A: TECHNICAL INVESTIGATION

2.1 Introduction

This chapter provides a brief overview of the operation of Unit C4 and summarises the key causative and consequential technical events of the incident. It also provides an overview of the approach taken in the technical investigation, introduces the technical investigation team, and explains the layout of Part A of the report.

2.2 Overview of Operation of Unit C4

In simple terms, Unit C4 operates as follows:

- Incoming coal is burned in a boiler, which heats water to create steam, which drives a turbine.
- The turbine spins a generator rotor at 3,000 revolutions per minute (rpm) to generate electricity.
- The electricity is passed through a generator transformer, which steps up the electrical voltage from 19.5 kV to 275 kV.[1]
- The electricity is then exported to Calvale substation, which is operated by Powerlink.

The operation of Unit C4 relies on two electrical systems: the Unit C4 AC (alternating current) system and the Unit C4 DC (direct current) system.

- The Unit C4 AC system supplies equipment required for the operation of the turbine and the generator (together referred to as the 'turbine generator').
- The Unit C4 DC system supplies equipment required for monitoring, control and protection of Unit C4. It also supplies backup equipment if AC supply is lost.

2.3 Summary of Key Causative Technical Events

The key causative technical events of the incident are summarised as follows:

(a) On the day of the incident, 25 May 2021, a replacement battery charger for the Unit C4 DC system had been specified, tested, and commissioned, and was being connected to Unit C4.

(b) At one of the planned steps in the connection process, the battery charger became the sole source of DC supply to Unit C4, which required it to respond instantly and maintain the DC voltage in Unit C4.

(c) The battery charger, however, had not been specified or tested to respond in this manner, nor was it capable of doing so under the operating conditions at the time. Consequently, it failed to maintain the DC voltage, which led to a partial collapse of DC voltage in the Unit C4 system.[2]

(d) The voltage collapse in Unit C4 directly led to the loss of AC supply to Unit C4.

[1] 'kV' denotes kilovolts, which equals 1,000 volts.

[2] The term 'collapse' (also 'partial collapse') is used to describe the sudden drop in voltage to ~120 V. The term 'loss' (also 'complete loss') is used to describe the drop in voltage to ~0 V.

(e) The loss of AC supply to Unit C4 then led to the complete loss of the DC supply to Unit C4.

(f) The Unit C4 automatic changeover switch, which, in the event of a loss of DC automatically restores DC supply to parts of the Unit C4 DC system, was damaged and inoperable in automatic mode.[3] Had the automatic changeover switch operated automatically, it could have altered the severity of the incident, although major component replacements are still possible under this scenario.

2.4 Summary of Key Consequential Technical Events

The loss of both the Unit C4 DC supply and AC supply directly led to the destruction of the turbine generator, summarised as follows:

(a) Due to the loss of AC supply, the valves controlling the flow of steam to the turbine closed, preventing further steam from entering and driving the turbine.

(b) Due to the loss of DC supply, all protection to Unit C4 was lost, including its ability to disconnect from the grid and shut down safely.

(c) Because the turbine generator was no longer being driven by steam, but was still connected to the grid, it went from generating electricity to consuming electricity – a condition referred to as 'motoring'. This resulted in the turbine generator continuing to spin.

(d) Due to the loss of both AC supply and DC supply, the pumps required for the safe operation of the turbine generator were unavailable (e.g., lubrication oil pumps, seal oil pumps, and cooling system pumps).

(e) The motoring of the unit over a 34-minute period, in combination with the loss of critical systems, such as lubrication oil pumps, directly led to the destruction of the turbine generator.

(f) The event culminated in large parts of the turbine generator (e.g., a two-tonne section of rotor) being ejected from Unit C4, in what is referred to as the 'turbine missile event'.[4]

(g) The generator remained connected to the grid for approximately 40 seconds after the turbine missile event. During this time, an electrical fault developed in the generator that led to arcing, causing almost three times the generator's rated power to be drawn from the grid. This fault was detected at Calvale substation, which then disconnected from the wider grid, hence also disconnecting Unit C4. This sequence of events initiated the destabilisation of the Queensland power grid.

[3] The Brady Heywood investigation determined that the automatic changeover switches in Callide C were prone to reliability issues, and therefore did not always operate successfully to restore supply as expected. In addition, The Brady Heywood investigation found that the part of the Unit C4 automatic changeover switch that provides automatic operating capabilities was damaged, and its fuses were blown and removed. Any one of these three conditions alone would have prevented automatic operation of the automatic changeover switch.
It is likely that the blown fuses and damage to the Unit C4 automatic changeover switch occurred during an incident in January 2021, and it is believed that these fuses were removed before the March 25 incident as part of the response to the January 2021 incident.

[4] A turbine 'missile event' is an industry term adopted by the Electric Power Research Institute that defines catastrophic failure of the rotating components of a turbine leading to projectiles in the turbine hall. https://www.epri.com/research/products/1006451

2.5 Approach to the Technical Investigation

The approach to the technical investigation was as follows:

- Physical evidence: A large quantity of physical evidence was collected after the destruction of the turbine generator. Components and debris of Unit C4 were strewn around the turbine hall and some had been ejected through the roof and were located outside the building. The collection of this physical evidence continued over several months.
- Metallurgical testing: Metallurgical testing of various components was undertaken.
- Electrical testing: Onsite testing of Unit C4's AC and DC systems was undertaken to determine how these systems operated on the day of the incident.
- Data analysis: Unit C4 is monitored by the integrated control and monitoring system (ICMS), which provides control and monitoring functionality for the unit. Data from this system, along with data from other systems, was analysed. It played a key role in determining the operation of the unit prior to and during the incident.[5]
- Interviews: Interviews with CS Energy personnel and others were conducted. We have relied on interview transcripts provided by Norton Rose Fulbright.
- Documentation: Considerable documentary evidence on the history and operation of Unit C4, as well as reports prepared by others, were analysed.

2.6 Technical Investigation Team

The technical investigation team was primarily as follows.

2.6.1 Lead Investigator

Dr Sean Brady CPEng, FIEAust is a forensic engineer, and the lead investigator of this incident.

2.6.2 Mechanical Investigation

Martin Boettcher CPEng, RPEQ, RPEV is a mechanical engineer with over 30 years' experience in power stations. This includes experience at Tarong North power station.

Mr Boettcher conducted the mechanical investigation, focusing on establishing the sequence of events that led to the failure of the turbine generator and other associated equipment.

2.6.3 Metallurgical Investigation

Dr David Tawfik CPEng has 18 years of specialist experience in engineering failure analysis, including material failures, mechanical failures, damage analysis, metallurgy and corrosion across various sectors.

Dr Tawfik conducted the metallurgical investigation. He observed and supervised the recovery and dismantling phase of the failed turbine generator, ensuring this process was performed in a forensically sound manner for the identification, collection and preservation of the relevant evidence. He also performed inspections on components and debris recovered from the incident, and planned

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[5] Although multiple signals were lost during the incident, the data that was available was retrieved and analysed.

and supervised the metallurgical investigation and mechanical testing programs undertaken by third party laboratories.

2.6.4 Electrical Investigation

Fiona Wingate BSc Eng, CEng, MIET is a chartered electrical engineer. She has over 25 years' experience with an emphasis on electrical power and high voltage power generation. She has led teams investigating control system and generation failures. She has experience in the specification, installation, commissioning and re-commissioning of generators and turbines.

Ms Wingate conducted the electrical investigation. She investigated the loss of the Unit C4 AC system and Unit C4 DC system conducted tests on site. Ms Wingate was assisted in her investigation by Alan Kinson and Dr Friedhelm Bonn in relation to the generator and generator transformer, respectively.

2.6.5 Battery Charger Investigation

Daniel Jessen BEng Mechatronics Engineering specialises in electronics design and product development. He has over 20 years' experience in electronics design and practical trade experience. He has led teams and carried out design and development work on a range of power converters, including inverters and battery chargers.

Mr Jessen conducted the Unit C4 battery charger investigation, conducting onsite tests on the Callide C battery chargers and AC and DC systems.

2.6.6 Cybersecurity Investigation

Chris Watson is a cybersecurity expert, specialising in forensic investigations. He was a detective in the computer forensic investigations team with the London Police Force prior to working in private practice. He brings over 30 years' experience in forensic investigations, cybersecurity, and financial crime.

Mr Watson conducted the investigation of CS Energy's cybersecurity systems and processes.

2.7 Layout of Part A: Technical Investigation

Part A is written for the non-technically trained reader.[6] Technical terms and jargon have been avoided, and many aspects of the incident have been simplified by only focusing on equipment and events that relate directly to the incident.

Broadly speaking, Part A is set out as follows.

- An overview of Unit C4, focusing only on equipment relevant to the incident, is presented in Chapter 3.
- The key events that occurred in the incident are discussed, specifically how the loss of the Unit C4 AC and DC electrical systems led to the catastrophic failure of the unit. This chapter primarily, therefore, focuses on the consequential damage that occurred on Unit C4.
- With this discussion then complete, the remainder of Part A, Chapters 5 to 9, focuses on the causative role played by the Unit C4 electrical systems and battery charger in the incident.

[6] In a number of places, footnotes provide further technical information for the technically trained reader.

- Chapter 10 Technical Conclusions provides the conclusions of the technical investigation.

Technical appendices provide more detail on the investigation process, the incident and its causes, and the evidence that support the opinions in this report. These appendices are intended for the technically trained reader.

3 OVERVIEW OF UNIT C4

3.1 Introduction

This chapter provides an overview of the key components of Unit C4 at Callide C power station, primarily focusing on the components that played a role in the incident on 25 May 2021.[7]

3.2 Overview of Unit C4 at Callide C Power Station

Callide C and Callide B power stations are located near Biloela, Queensland, Australia.[8] Callide C power station is comprised of two units: Unit C4 and Unit C3. Callide B power station also has two units: Unit B2 and Unit B1.

Each of the four units has its own turbine generator, which are located in a single building referred to as the turbine hall.[9] Figure 1 shows the arrangement of the four units.

Figure 1 Site layout of Callide B and C power stations showing position of turbine generators[10]

[7] This chapter and the one that follows present a set of simplified illustrations to assist the non-technically trained reader to understand the key components of Unit C4 and the role they played in the incident. They should not be considered an accurate representation of the physical unit.

[8] While the term 'Callide power station' is often used to describe the site, the site is comprised of two power stations, Callide B and Callide C.

[9] The term 'turbine generator' is a collective term for the turbine and generator.

[10] Photograph: Google, © 2024 CNES / Airbus

The incident resulted in the catastrophic failure of Unit C4. The other units on the site played no significant role in the incident and will be discussed only where relevant.

3.3 Overall Operation of Unit C4

Unit C4 is a coal-fired power generator.[11] Coal is burned in a boiler, which heats water and turns it into high pressure steam. This steam expands through a turbine and applies force to blades that drive the rotor at 3,000 revolutions per minute (rpm). The expanded steam is then condensed into water (in the condenser) and returned to the boiler for the cycle to repeat. Inside the generator, the spinning of the rotor at 3,000 rpm converts rotational energy into electrical energy. This electricity is exported to Calvale substation, which forms part of the Queensland power grid. Figure 2 illustrates the general arrangement of the Unit C4 turbine generator.

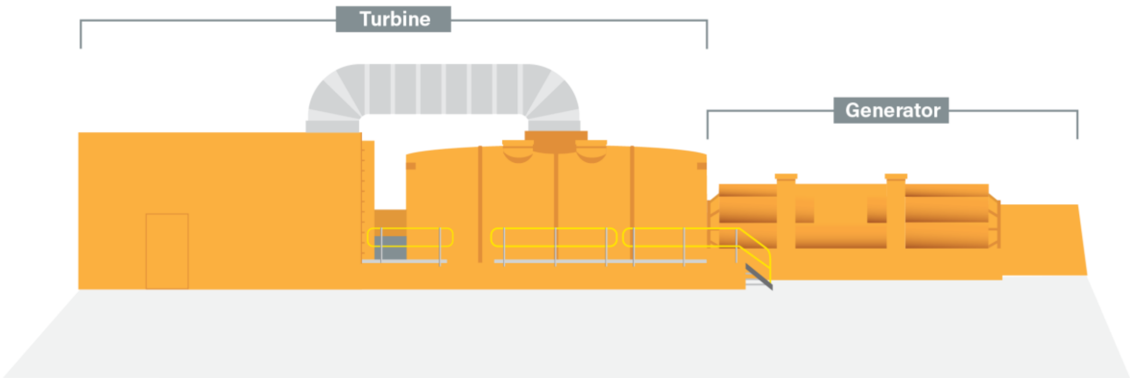


Figure 2 Unit C4 general arrangement of the turbine generator

The turbine generator primarily consists of a rotor (comprised of several component rotors bolted together at 'couplings'), as depicted in Figure 3. The couplings of the rotors have been omitted from this diagram for simplicity.[12]

[11] Unit C4 is a black coal-fired unit of supercritical pressure and single reheat design, with a capacity of 424 MW.

[12] The shaft is coupled in the following locations: turbine stub shaft to HIP shaft; between HIP shaft and LP shafts; between LP shaft and generator shafts; and between generator shaft and generator stub shaft.

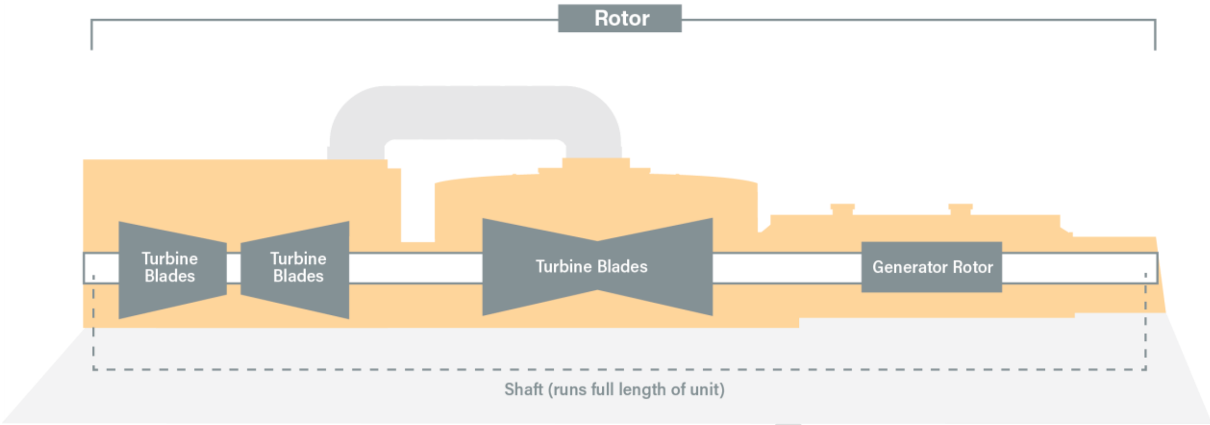


Figure 3 Rotor running through the turbine generator

The turbine blades and generator rotor components are attached to a central core called a 'shaft'. The whole assembly is referred to as a 'rotor'. As will be discussed later, the shaft is held in place inside the turbine generator by bearings.

3.4 Mechanical Overview

3.4.1 Turbine

The 'turbine' is made up of three turbines: the high pressure (HP) turbine, the intermediate pressure (IP) turbine, and the low pressure (LP) turbine. The HP and IP turbines are located inside a common casing and are referred to jointly as the 'HIP turbine'. The arrangement of the turbines is shown in Figure 4.

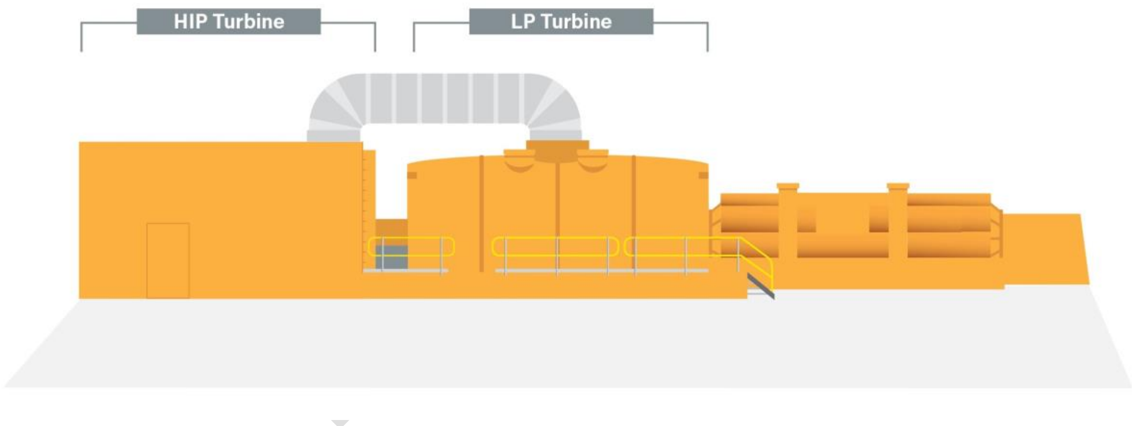


Figure 4 Arrangement of the various turbines

Steam from the boiler flows through the HP turbine, then returns to the boiler for reheating. It then flows through the IP turbine and into the LP turbine. Each turbine is comprised of a series of blades that run along the rotor, and the steam applies force to these blades, rotating the rotor at 3,000 rpm. The three turbines are shown schematically in Figure 5.

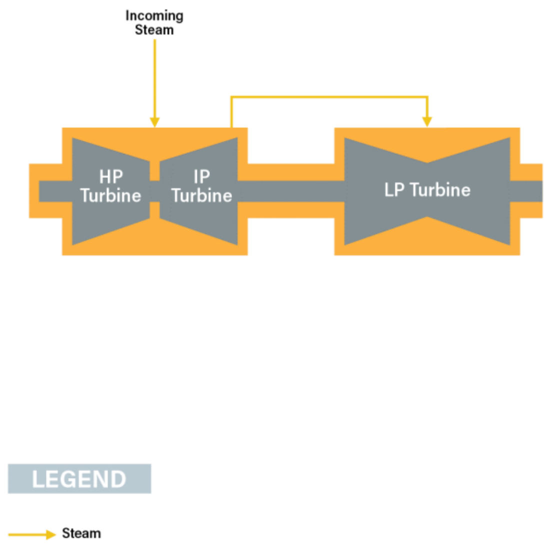


Figure 5 HP, IP and LP turbines

3.4.2 Steam Valves

Steam from the boiler enters the turbine via isolation steam valves and control steam valves (referred to in this report as 'steam valves'), which are operated by a hydraulic oil system.[13] The steam valves and hydraulics system are illustrated in Figure 6.

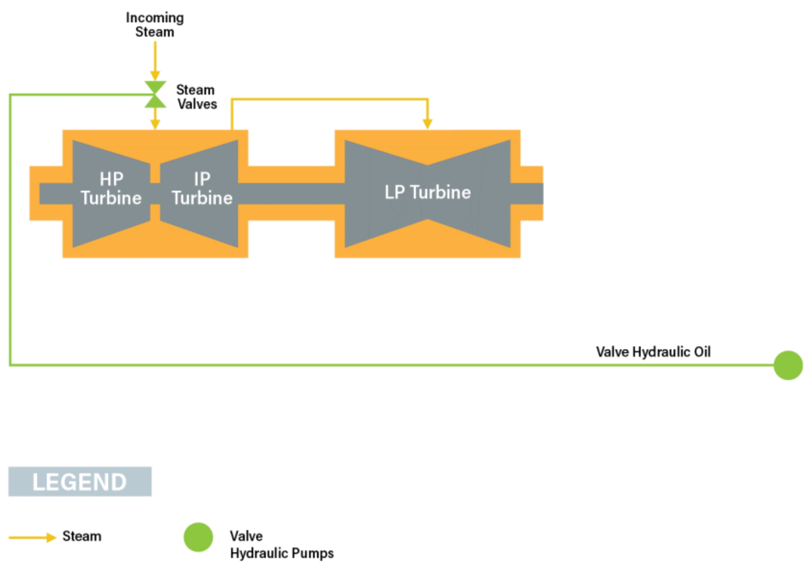


Figure 6 Steam valves and valve hydraulics

[13] While this report uses the term 'steam valves' and illustrates a single steam supply, the physical arrangement is more complex. Steam to the HP turbine goes through the main stop valves (MSVs) and turbine control valves (TCVs). The exhaust of the HP turbine goes back to the boiler and gets reheated. It returns to the IP turbine via the reheat stop valves (RSVs) and intercept control valves (ICVs).

These valves are of a 'fail-safe' design, meaning that hydraulic oil pressure is required to keep them open. In the event of a loss of hydraulic oil supply, large mechanical springs quickly force the valves closed, which immediately shuts off the flow of steam to the turbines.

3.4.3 Generator

The generator is comprised of a rotor and a stator. For illustrative purposes, a typical generator is shown in Figure 7.[14]

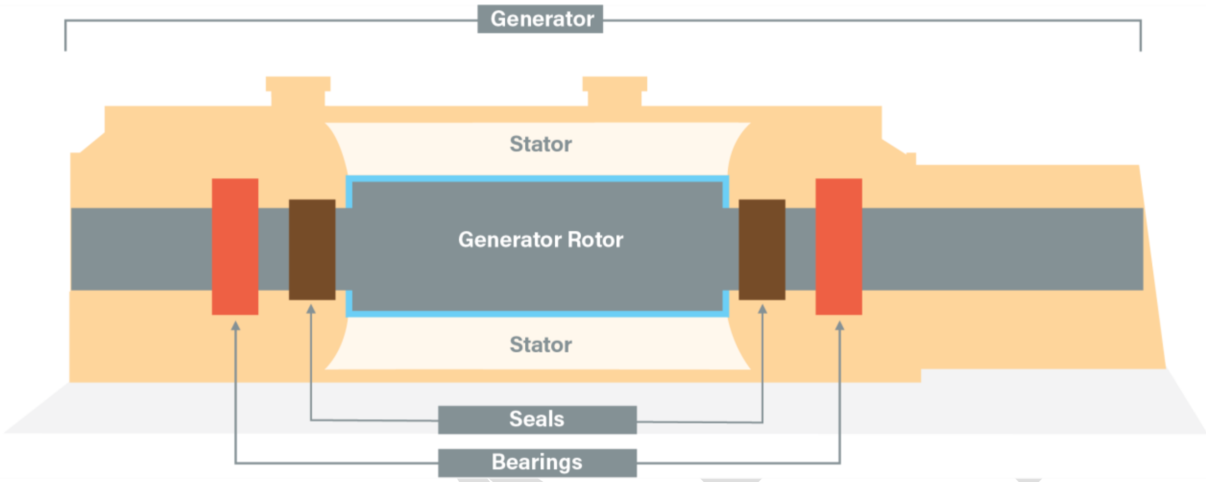


Figure 7 Typical generator, indicating generator rotor and stator

The generator rotor rotates, while the stator remains stationary.[15] The rotation of the generator rotor inside the stator, driven by the turbine, generates electricity.[16]

When operating, the generator also produces heat, which is removed by two cooling systems. The generator stator is cooled by water, while the generator rotor is cooled using pressurised hydrogen gas contained inside the generator.[17]

3.4.4 Bearings

Bearings hold the shaft in place at eight locations along its length, as indicated in red in Figure 8.[18]

[14] Hydrogen indicated in blue.

[15] The generator rotor consists of: a central shaft (single forging), slip rings and connections, the rotor electrical coils and their insulation, the cooling fans, the coil retaining rings, and balance weights.

[16] In simple terms, an electric current is passed through the rotor winding coils, which creates a magnetic field around the rotor. The movement of this magnetic field (as a result of the turbine rotating the generator rotor) results in an electric current flowing through the conductors of the stator. In other words, the generator operates on the principle that moving a conductor in an electric field generates electricity in the conductor. In this case, however, it is the magnetic field that is moving (the generator rotor), and the conductor (the stator) is staying still.

[17] The stationary part of the generator is cooled by ultra-pure water, called 'stator coolant', which is pumped through hollow stator conductor bars to absorb and remove heat. The hydrogen gas is cooled in the hydrogen coolers using treated cooling water. The treated cooling water (that flows in a closed circuit) is cooled by the auxiliary cooling water system, which rejects its heat in the cooling towers. The main cooling water circuit is separate to, but uses the same cooling towers as, the auxiliary cooling water system.

[18] There are seven radial bearings along the shaft, and one thrust bearing located between the HIP and LP turbines.

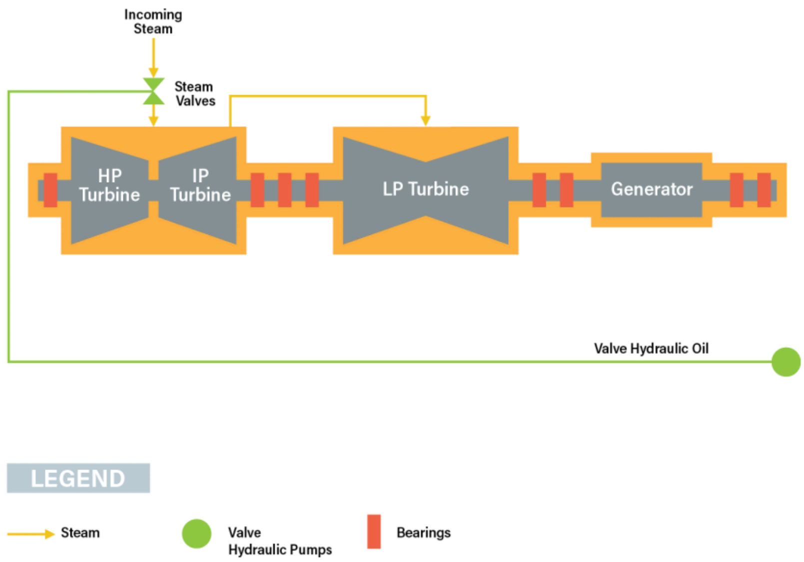


Figure 8 Bearing locations

The bearings are made of steel, and have a soft metal lining known as 'white metal'.[19] Each bearing is made up of two semicircular 'collars', which form a ring around the shaft to hold it in place. An exploded view of the shaft and bearings is illustrated in Figure 9.

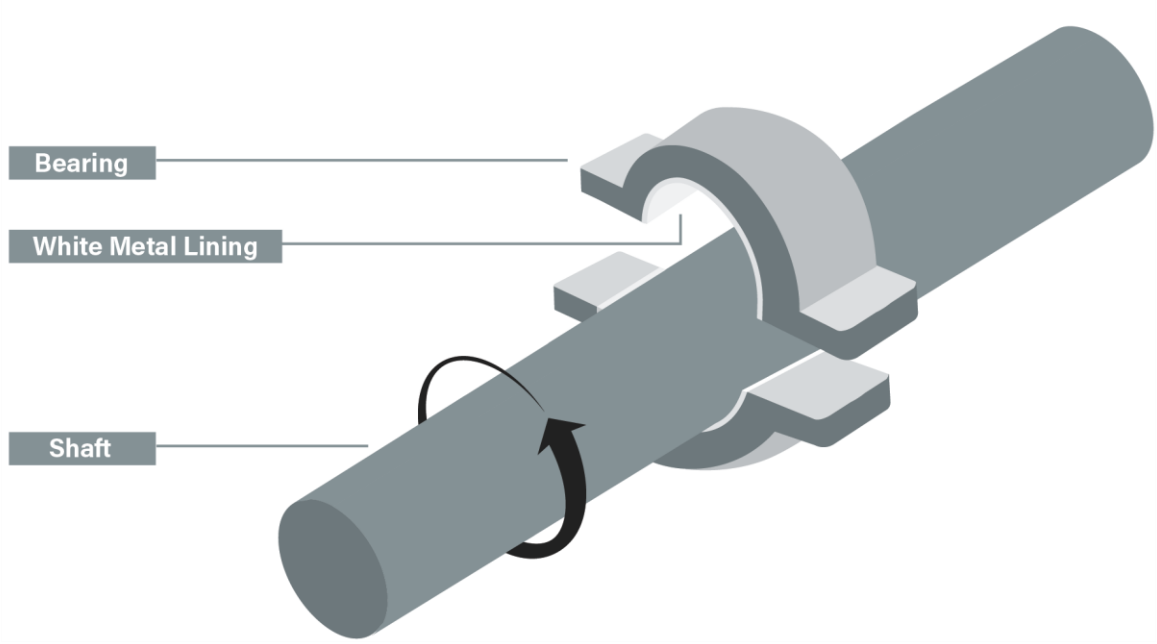


Figure 9 Illustration of shaft and bearing

[19] The white metal lining is a soft metal layer on the inside of the bearing. If the bearing loses lubrication oil, this layer will wear first, minimising damage to the rotor, which is made from 'harder' steel.

Lubrication oil is pumped into the gap between the shaft and the bearing to form a thin film of oil. The shaft spins on this thin film of oil, ensuring no metal-on-metal contact. The lubrication oil also removes heat generated from the rotation of the shaft.[20] Figure 10 illustrates the lubrication oil pumps, with the oil supply shown in red.[21]

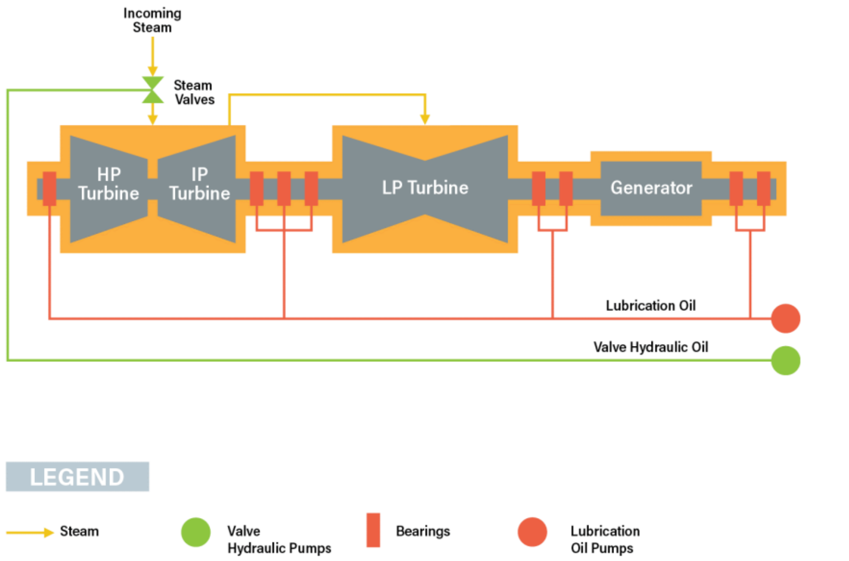


Figure 10 Bearings and lubrication oil pumps

A loss of lubrication oil pressure (for example, due to the loss of the lubrication oil pumps), will result in the shaft directly touching the bearing metal. This can result in physical damage to the shaft and the bearing, as well as generate significant heat.

3.4.5 Generator Seal Oil

Pressurised hydrogen gas is contained inside the generator to keep the rotor cool as it spins.[22] To ensure hydrogen does not escape, a seal is created by pumping pressurised oil into the very small gap between the shaft and generator casing at each end of the generator.[23] This oil is referred to as 'seal oil', and its pressure is maintained by a continuously operating seal oil pump, as illustrated in Figure 11.[24]

[20] Heat is removed from the lubrication oil system in the lubrication oil coolers, with the heat taken away by the auxiliary cooling water system.

[21] The unit has two AC lubrication oil pumps and one emergency DC lubrication oil pump.

[22] The hydrogen transfers the heat to the treated cooling water system in the hydrogen coolers. It also assists in the removal of heat from the stator.

[23] Where the shaft enters the generator, tight clearances are maintained between the shaft and generator casing. It is these tight clearances in combination with the oil that creates the oil seal.

[24] Unit C4 has one AC seal oil pump, one emergency DC seal oil pump, and a small AC recirculating pump.

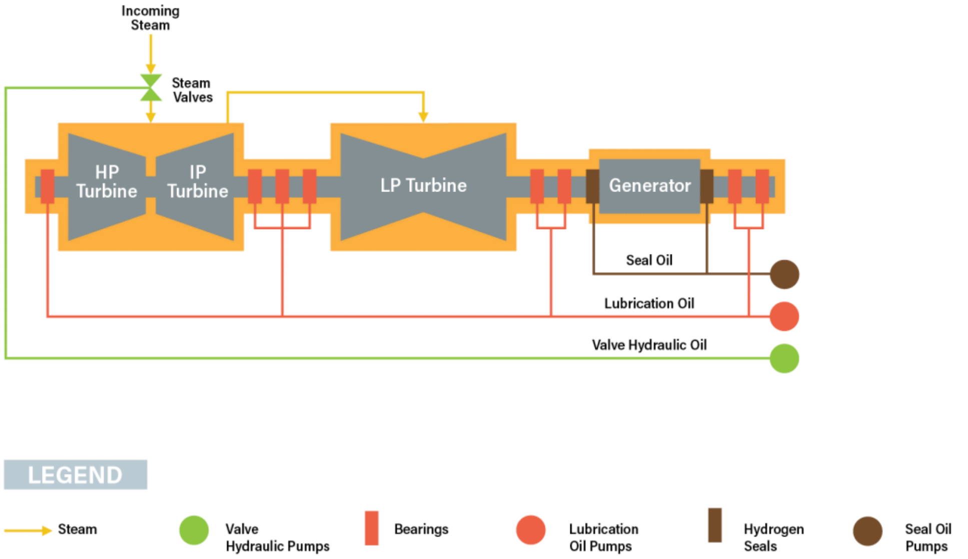


Figure 11 Generator hydrogen seals and seal oil pumps

3.4.6 Generator Circuit Breaker

Electricity generated by the generator is exported to the Queensland power grid, via a switch called the generator circuit breaker, as illustrated in Figure 12.

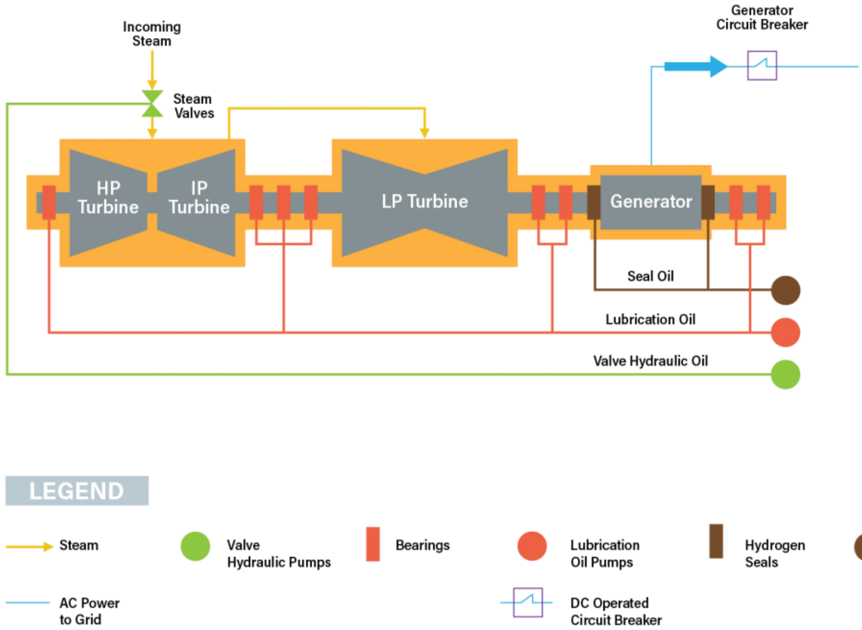


Figure 12 Generator circuit breaker

The generator circuit breaker both connects and disconnects the unit from the grid. It is a critical safety device because successfully disconnecting from the grid is a key requirement when shutting a unit down safely.[25]

The generator circuit breaker is located in the turbine hall, one level below the turbine generator.

3.4.7 Generator Transformer

The role of the generator transformer is to convert electricity produced by the generator from 19.5 kV to 275 kV, which is the transmission grid voltage, see Figure 13.

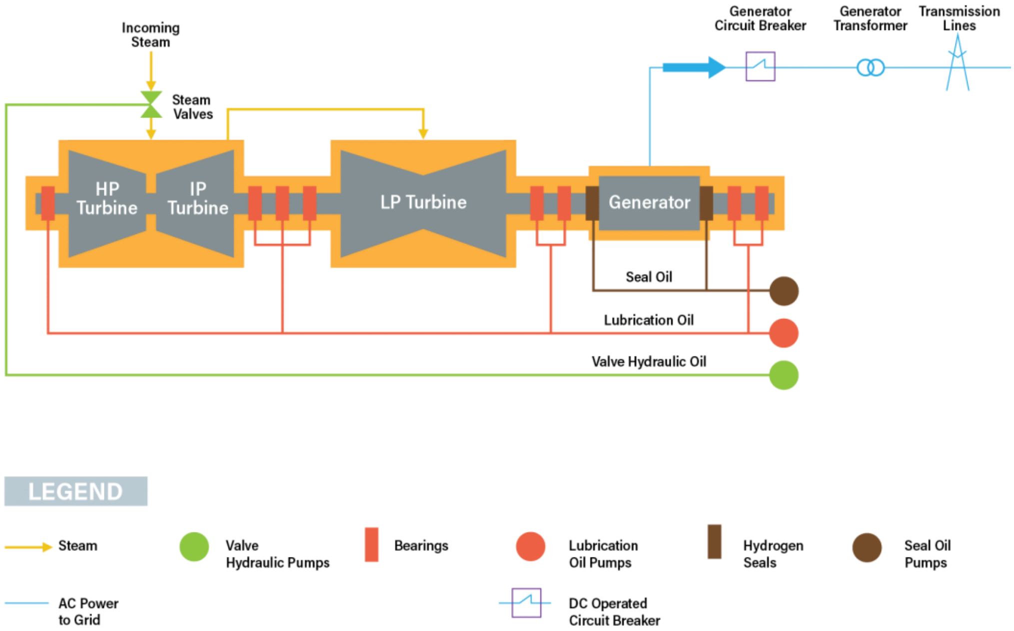


Figure 13 The generator transformer

During operation, the generator transformer produces heat, which is removed by its own cooling system.

3.4.8 Calvale Substation

The electricity generated from Unit C4 is exported to Calvale substation, depicted in Figure 14.

[25] At Calvale substation, which is operated by Powerlink, there are also transmission system breakers. Unit C4 does not have a generator transformer HV breaker.

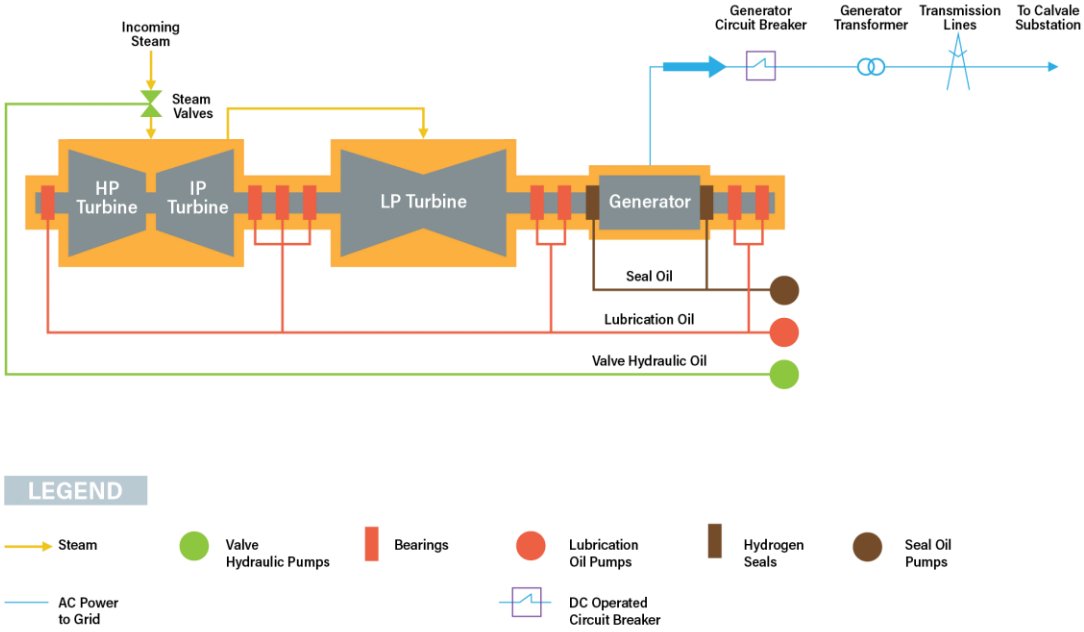


Figure 14 Calvale substation

Calvale substation is operated by Powerlink, and it forms part of the Queensland power grid.

3.5 Electrical Overview

3.5.1 Callide C Electrical System

The Callide C electrical system supplies plant and equipment at Callide C. It is comprised of two electrical systems: the Callide C AC system and the Callide C DC system. They are separate systems but have some interdependencies.

They perform different roles within the power station:

- The Callide C AC system connects to the grid and, in simple terms, supplies the equipment necessary for the turbine generators to generate electricity.[26]
- The Callide C DC system is supplied from battery chargers and batteries, which work together to supply a range of control, monitoring, and protection systems. These systems are critical for the safe operation of Units C3 and C4, and can be thought of as the 'brain and life-support' of the units.

3.5.2 Callide C AC System

The Callide C AC system can be divided into three subsystems:

- Unit C3 AC system, which supplies the AC equipment associated with Unit C3.
- Unit C4 AC system, which supplies the AC equipment associated with Unit C4.

[26] In normal operation, the AC system receives its AC supply from the unit generator. If a unit generator is disconnected from the grid, its AC system receives supply from the grid instead.

- Station AC system, which supplies AC equipment common to both Unit C3 and Unit C4. It is also available as a backup supply for Unit C3 and Unit C4.

3.5.3 Callide C DC System

The Callide C DC system is also divided into three subsystems:

- Unit C3 DC system, which supplies the DC equipment associated with Unit C3.
- Unit C4 DC system, which supplies the DC equipment associated with Unit C4.
- Station DC system, which supplies DC equipment common to both Unit C3 and Unit C4. It is also available as a backup supply for Unit C3 and Unit C4.

3.5.4 Configurability in the AC and DC Systems

Each of these three AC systems and these DC systems can be configured to suit the operational needs of the power station.

The configurability affords a high level of robustness within the Callide C electrical system. For example, if scheduled maintenance is being performed on equipment in the Unit C4 DC system, supply to other equipment can be routed from the Station DC system.

Changes to the configuration of the Callide C electrical system is carried out in accordance with a formal, pre-planned sequence of steps, referred to as a 'switching sequence'. Each time a configuration to the electrical system is needed, a formal process is followed to develop a switching sequence that, when executed, achieves the desired configuration.

3.5.5 Unit C4 AC System

While the Unit C4 AC system supplies most of the equipment necessary for Unit C4 to generate electricity,[27] it also supplies the steam valve hydraulics, the main lubrication oil pumps, and the main seal oil pump, which are most relevant to the incident, see Figure 15.

[27] This includes large equipment such as fans, mills and conveyors.

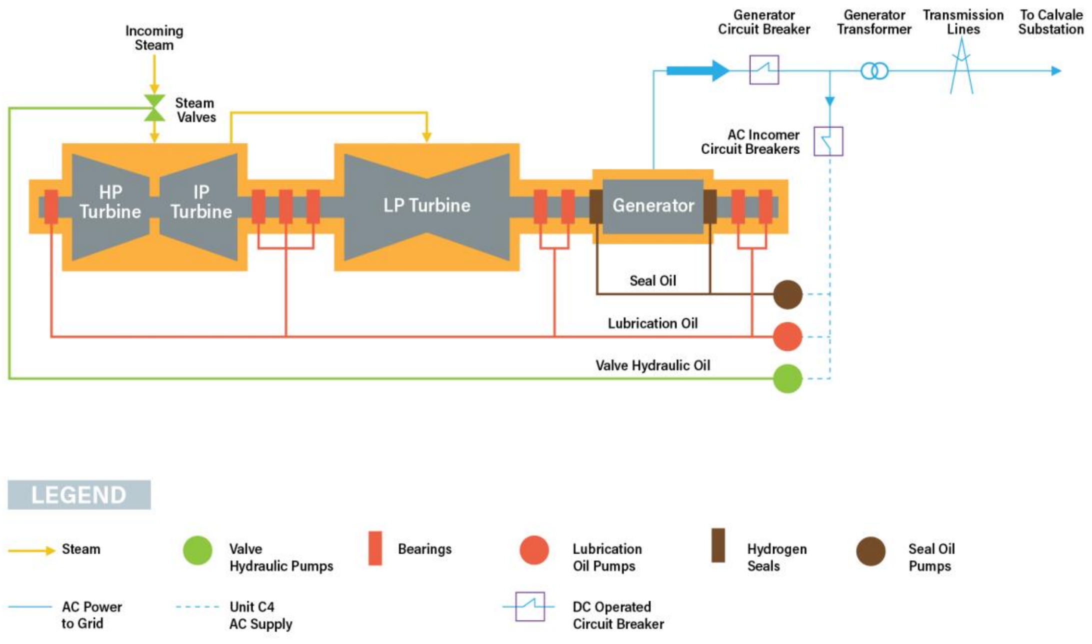


Figure 15 Simplified Unit C4 AC system

The figure above also illustrates how, before supplying Unit C4's large equipment, the AC supply passes through AC circuit breakers (known as the AC 'incomer circuit breakers').[28] If a fault develops in the AC system, these AC incomer circuit breakers open automatically, tripping the AC supply to Unit C4's equipment.

3.5.6 Unit C4 DC System

The Unit C4 DC system is supplied by a battery charger and a battery, and is illustrated in Figure 16.

[28] There are multiple transformers in the AC system, which are omitted from this diagram for simplicity.

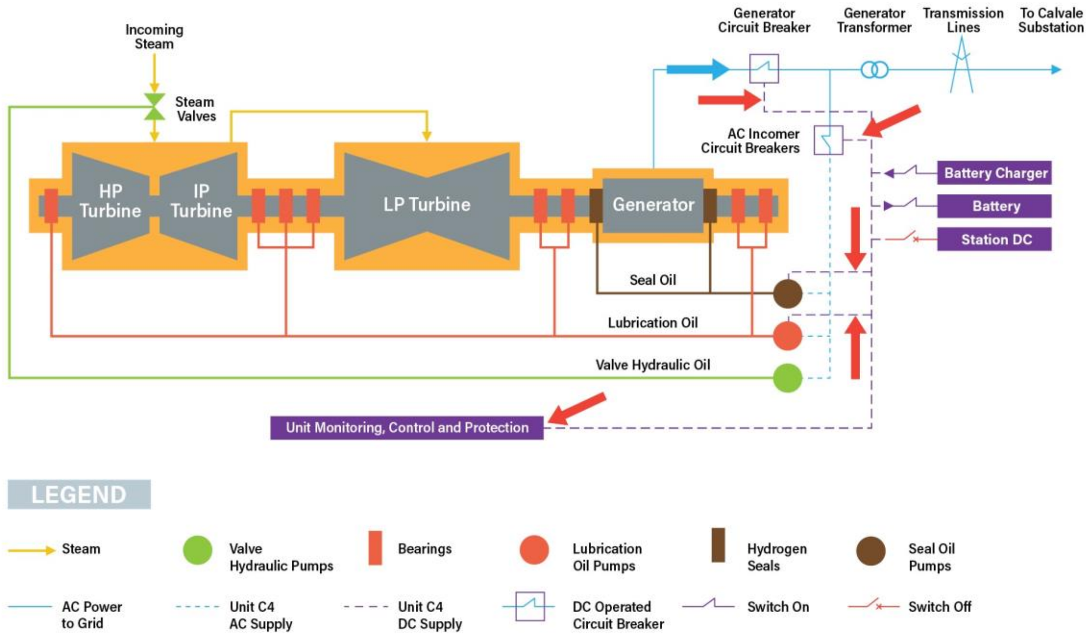


Figure 16 Simplified Unit C4 DC system

As indicated in the figure above, the Unit C4 DC system supplies:

- The generator circuit breaker, which connects and disconnects the Unit C4 generator from the grid. (The generator circuit breaker requires DC supply to operate.)
- The AC incomer circuit breakers, which connect and disconnect AC supply from the Unit C4 AC system. (The AC incomer circuit breakers require DC supply to operate.)[29]
- The emergency seal oil pump, which operates in the event of a loss of AC supply to the main seal oil pump.
- The emergency lubrication oil pump, which operates in the event of a loss of AC supply to the main lubrication oil pumps.
- Unit monitoring, control and protection systems, including the X protection and the Y protection systems, which will be discussed further in Chapter 5.

3.5.7 DC Battery Charger and Battery

Unit C3, Unit C4 and Station each have two separate DC supplies: a battery charger and a battery. Figure 17 shows the Unit C4 battery charger and battery.

[29] In addition to the generator circuit breaker and AC incomer circuit breakers, the DC system also supplies other AC switchgear, which can automatically reconfigure the AC system.

(a) Unit C4 battery charger *(b) Unit C4 battery*

Figure 17 Unit C4 battery charger and battery

The Unit C4 battery charger is supplied by the AC system, and, in simple terms, converts AC supply into DC supply. Although the term 'battery charger' suggests its role is to simply charge the battery, its function is more nuanced. Despite its name, it is the battery charger that primarily provides DC supply to all the equipment in the DC system, while also maintaining the battery at a full state of charge.[30]

The battery charger, therefore, should be considered as the primary source of supply to the DC system.

The role of the battery in the DC system is to provide important redundancy if the battery charger stops operating. For example, if the battery charger loses its AC supply, it will shut down, and if this occurs, the battery takes over the role of providing DC supply to the system.

3.5.8 Automatic Changeover Switch

Unit C4 has a switch known as the 'automatic changeover switch' that operates if Unit C4 loses DC supply. If DC supply is lost to Unit C4, the Unit C4 automatic changeover switch can respond and automatically 'change over' to supply part of Unit C4 from Station DC.[31]

The automatic changeover switch has control circuitry that detects the loss of DC supply, and a motorised switch that operates to reroute Station DC supply to parts of the Unit C4 DC system.[32] Figure 18 shows the Unit C4 automatic changeover switch.

[30] While it is the battery charger that primarily provides the DC supply, there are times when the battery charger and battery work together to supply the DC system. This operation is discussed further in Chapter 5.

[31] Station and Unit C3 also have automatic changeover switches.

[32] The automatic changeover switch is also capable of being operated manually.

Figure 18 Unit C4 automatic changeover switch

On the day of the incident, the Unit C4 automatic changeover switch was damaged and inoperable in automatic mode.

3.5.9 Emergency Diesel Generator

If AC supply is lost to Unit C3, Unit C4 or Station, an emergency diesel generator can operate to restore AC supply to critical equipment.[33] The emergency diesel generator is shown in Figure 19.

Figure 19 Unit C4 emergency diesel generator

3.6 Chapter Summary

This chapter summarised the key components of Unit C4 that are relevant to the incident, presenting them in a simplified diagram, see Figure 20.

[33] The emergency diesel generator operates in response to a loss of AC supply in Station. Restoration of AC supply to the Unit C3 or Unit C4 is achieved by configuring the AC system to supply each unit from the Station AC system.

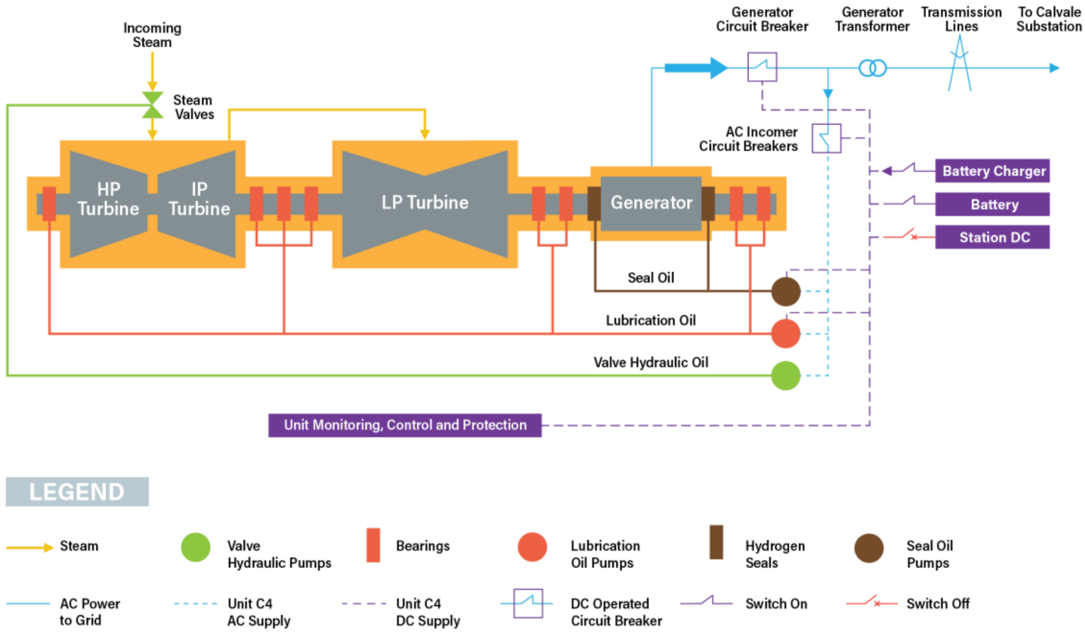


Figure 20 Simplified diagram of Unit C4 systems relevant to the incident

In the next chapter, this diagram is used to explain how the loss of AC and DC supply to Unit C4 led to its catastrophic failure.

4 KEY EVENTS AND TECHNICAL CAUSES OF THE INCIDENT

4.1 Introduction

This chapter provides an overview of the key events and technical causes of the incident. Subsequent chapters discuss these events in more detail, and a technical explanation of the events is provided in appendices AXXX and AXX.

This chapter examines:

- Collapse and loss of DC supply.[34]
- Loss of AC supply.
- Motoring of the unit.
- Catastrophic failure of the unit.

4.2 The Collapse and Loss of Unit C4 DC Supply

4.2.1 Background to 25 May 2021

In the 18 months leading up to the incident, an upgrade program had been initiated to replace the battery chargers at Unit C3, Unit C4 and Station. Prior to the incident, the Unit C3 and Station battery chargers had been replaced and successfully brought back into service.

While the Unit C4 battery charger was out of service for replacement, Unit C4 was supplied from Station DC, as depicted in Figure 21.

[34] In the incident, the Unit C4 DC voltage collapsed from ~243 V to ~120 V. It then decayed rapidly to ~0 V.

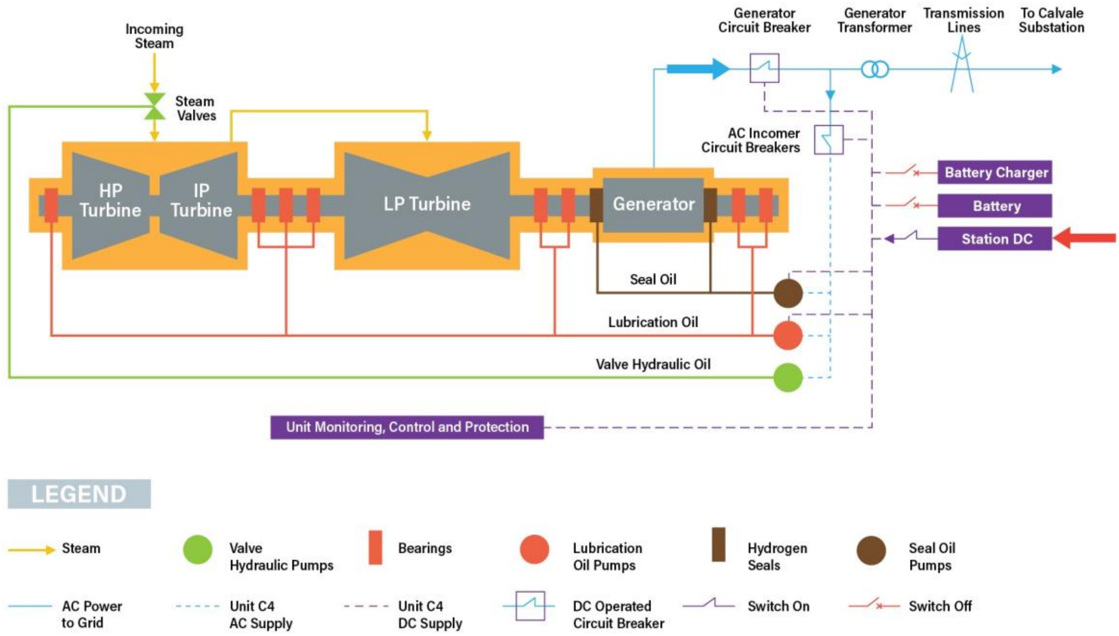


Figure 21 Unit C4 DC system supplied from Station

On the day of the incident, the replacement Unit C4 battery charger and existing battery were ready to be reconnected to the unit.

4.2.2 The Switching Sequence

The reconnection of the battery charger and battery was undertaken using a process called 'switching'. Switching is the formal process of making changes to a unit's electrical configuration, and it is carried out in accordance with a series of prescriptive sequential steps, which is referred to in this report as a 'switching sequence'. While this switching sequence was being executed, Unit C4 was operational and exporting power to the grid.

By 1:32 pm on the day of the incident, the switching sequence was in progress.[35] The next step in the sequence was to connect the replacement Unit C4 battery charger to Unit C4, see Figure 22.

[35] In this report, all time is expressed in Australian Eastern Standard Time (AEST).

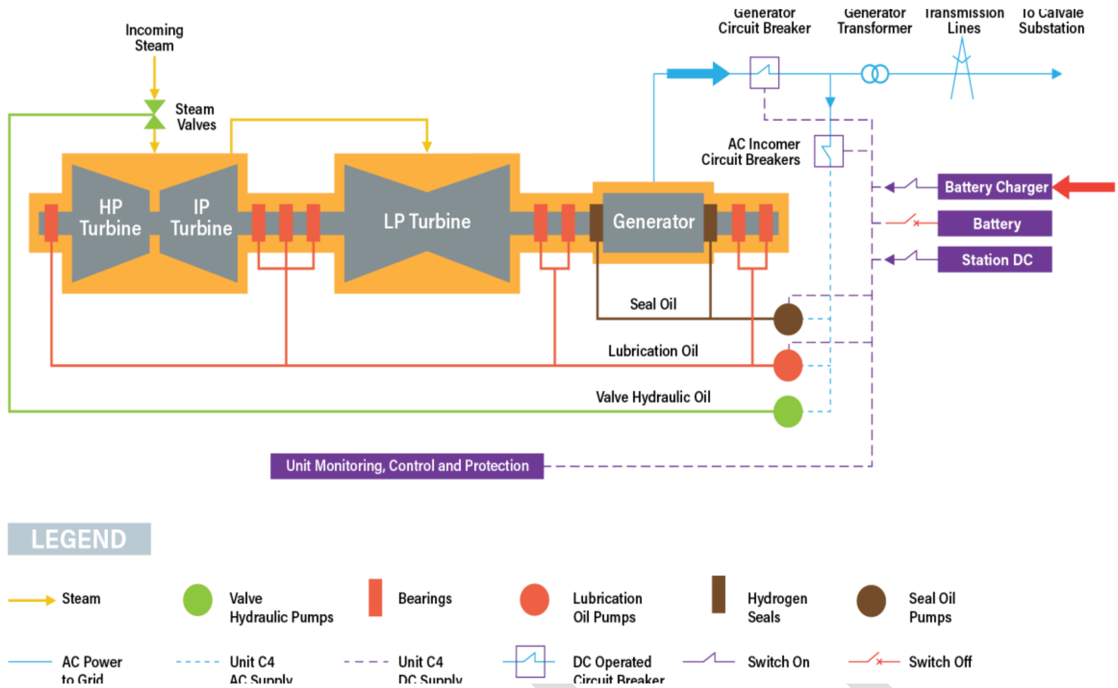


Figure 22 Unit C4 battery charger connected to DC system

This step was completed successfully, resulting in the unit now having two potential DC supplies: the Station DC system and the Unit C4 battery charger.[36] The next step was to disconnect the Station DC system from Unit C4, see Figure 23.

[36] The Station DC system supply is comprised of the Station battery charger and battery.

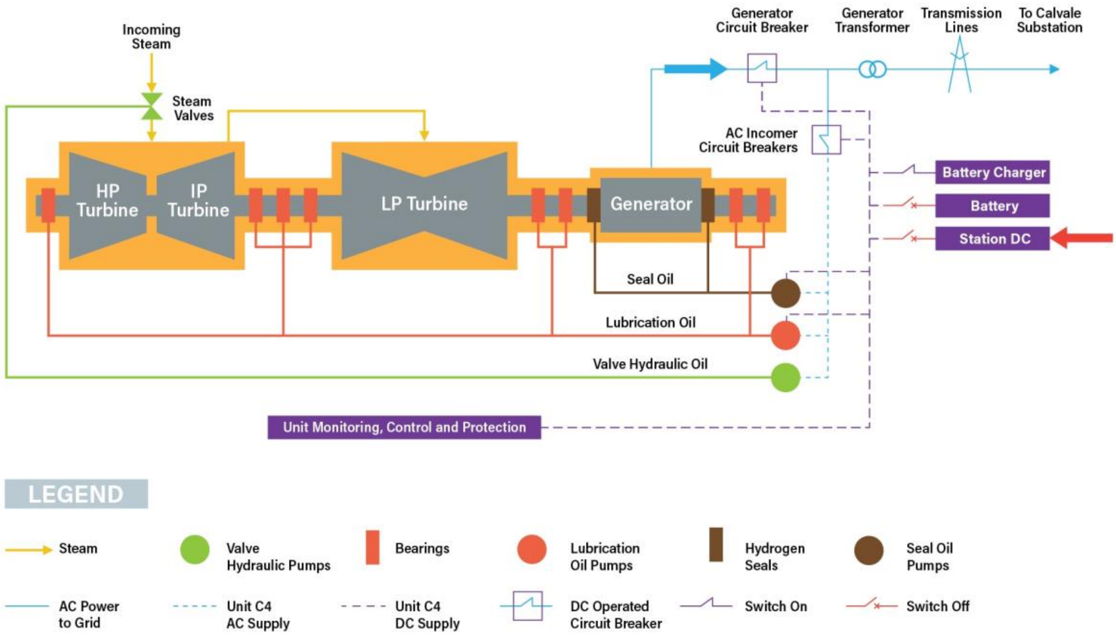


Figure 23 Unit C4 DC system disconnected from Station and supplied solely by the replacement Unit C4 battery charger

Disconnecting the Station DC supply resulted in the Unit C4 battery charger becoming the sole source of DC supply to Unit C4. This step placed an implicit requirement on the battery charger to respond instantly and maintain the voltage in the Unit C4 DC system. Despite this being an implicit requirement of the switching sequence, the ability of the battery charger to meet this requirement had not been specified or tested by CS Energy.[37]

4.2.3 Collapse and Loss of DC Supply

When Station DC was disconnected, the voltage in the Unit C4 DC system instantly collapsed from ~243 V to ~120 V. It then decayed rapidly over a period of two seconds to ~0 V, leading to a complete loss of DC supply to Unit C4.[38] This collapse of the DC supply occurred because the Unit C4 battery charger failed to maintain the DC voltage in the DC system. This loss of DC supply is illustrated by the grey line in Figure 24.

[37] The Brady Heywood investigation determined that under the specific conditions on the day, the battery charger was not capable of responding instantly and maintaining the voltage in the Unit C4 DC system.

[38] As will be discussed later in this report, the collapse of the Unit C4 DC system voltage to ~120 V directly led to the loss of the Unit C4 AC supply to ~0 V, which in turn led to the loss of the Unit C4 DC supply, i.e., the voltage decayed to ~0 V.

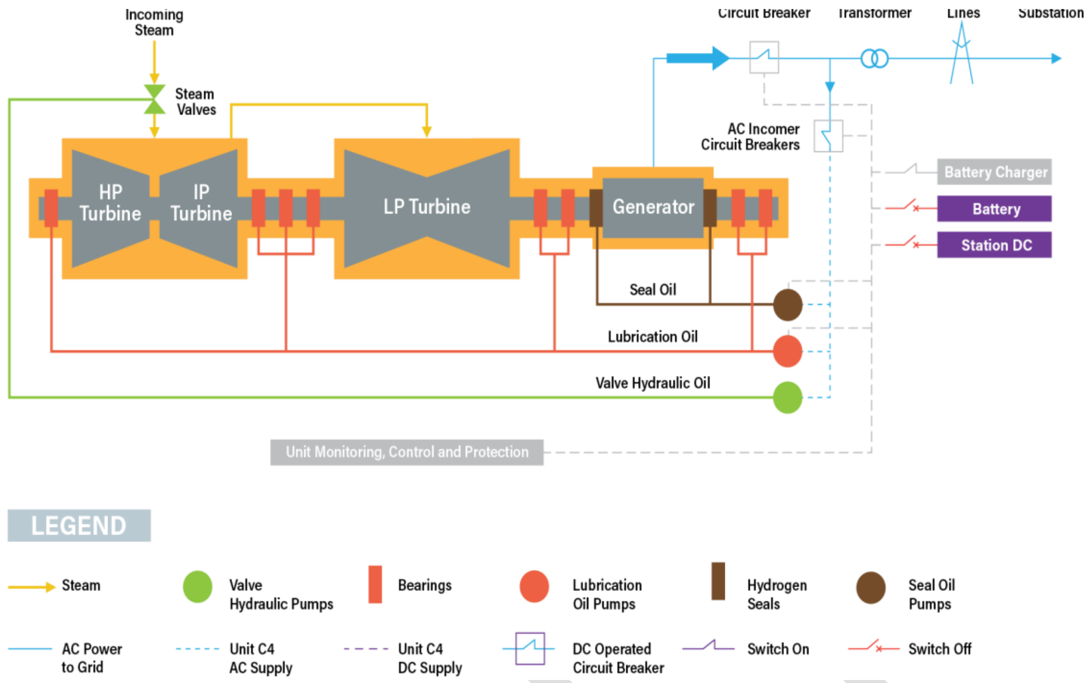


Figure 24 Loss of Unit C4 DC supply

4.2.4 Consequences of Collapse and Loss of DC Supply

The collapse and subsequent loss of DC supply to Unit C4 resulted in an immediate loss of several critical systems, as shown in Figure 25.[39]

[39] The consequences of the collapse and subsequent loss of the Unit C4 DC supply is discussed later in this report.

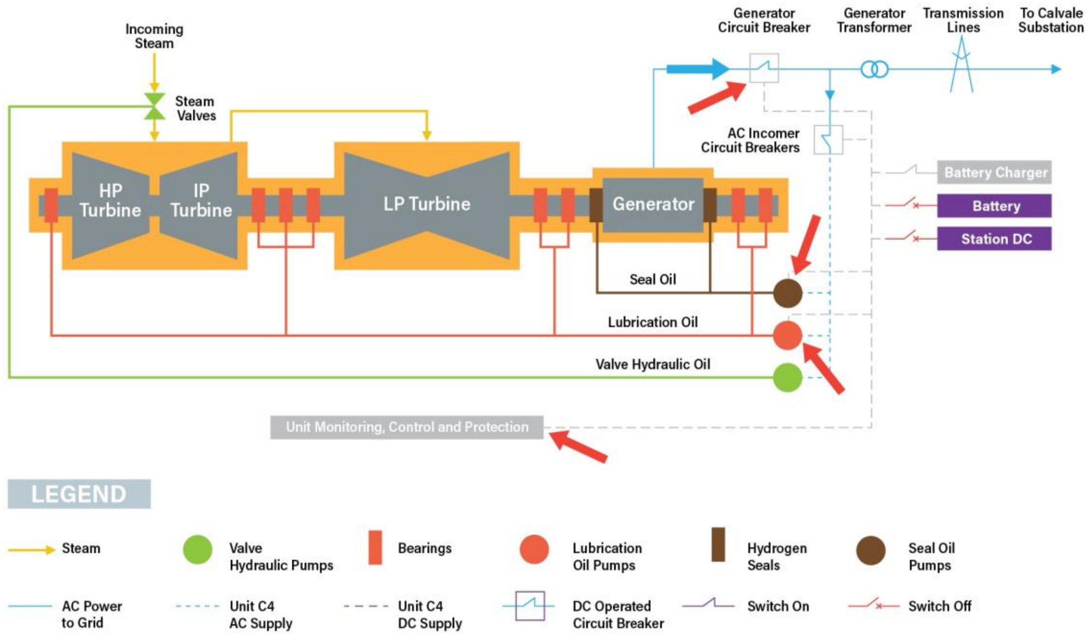


Figure 25 Loss of critical DC systems

These critical Unit C4 systems included:

- The generator circuit breaker, the loss of which meant the unit could not be disconnected from the grid by the Callide operators.
- The emergency oil pumps for seal oil and lubrication oil. The loss of these backup pumps was not an immediate issue because the lubrication and seal oil pressures were still being maintained by the AC pumps.
- The protection systems, which detect faults or issues with the turbine generator and respond accordingly. The loss of protection systems meant the unit could no longer be monitored, shut down safely, or automatically disconnected from the grid.

4.3 Unit C4 Automatic Changeover Switch Failed to Restore Unit C4 DC Supply

As discussed in Chapter 3, Unit C4 has an automatic changeover switch. But this switch was damaged and inoperable in automatic mode. Therefore, it did not operate, and DC supply to Unit C4 was not restored.

Had the automatic changeover switch been operational, it may have responded to the loss of DC voltage and automatically changed over to supply part of the Unit C4 DC system from Station. This may have altered the severity of the incident, although major component replacements are still possible under this scenario.

4.4 Loss of Unit C4 AC Supply

4.4.1 Cause of Loss of AC Supply

The voltage collapse in the Unit C4 DC system directly led to the loss of Unit C4 AC supply. How this occurred will be discussed in detail in Chapter 8, but in simple terms, equipment in the DC system that monitors the AC system for faults, misinterpreted the DC voltage collapse as a fault in the AC system. The DC equipment then responded by tripping the AC incomer circuit breakers, causing the loss of AC supply to the unit, see Figure 26.

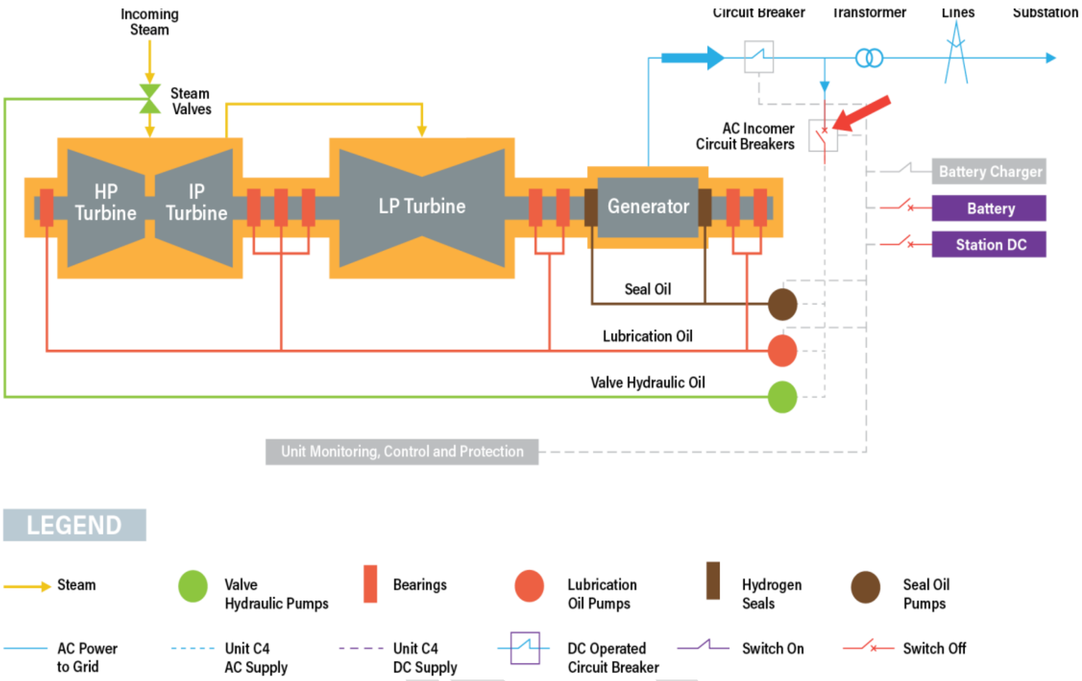


Figure 26 AC incomer circuit breakers trip AC supply to the unit

4.4.2 Consequences of Loss of AC Supply

The loss of AC supply to Unit C4 had five key consequences.[40]

First, it led to the failure of the hydraulic oil system that operates the steam valves, causing the valves to close (due to their fail-safe design). This meant steam was no longer entering and driving the turbine, see Figure 27.

[40] These consequences did not necessarily occur sequentially as represented in this report, but they are discussed and illustrated sequentially for simplicity.

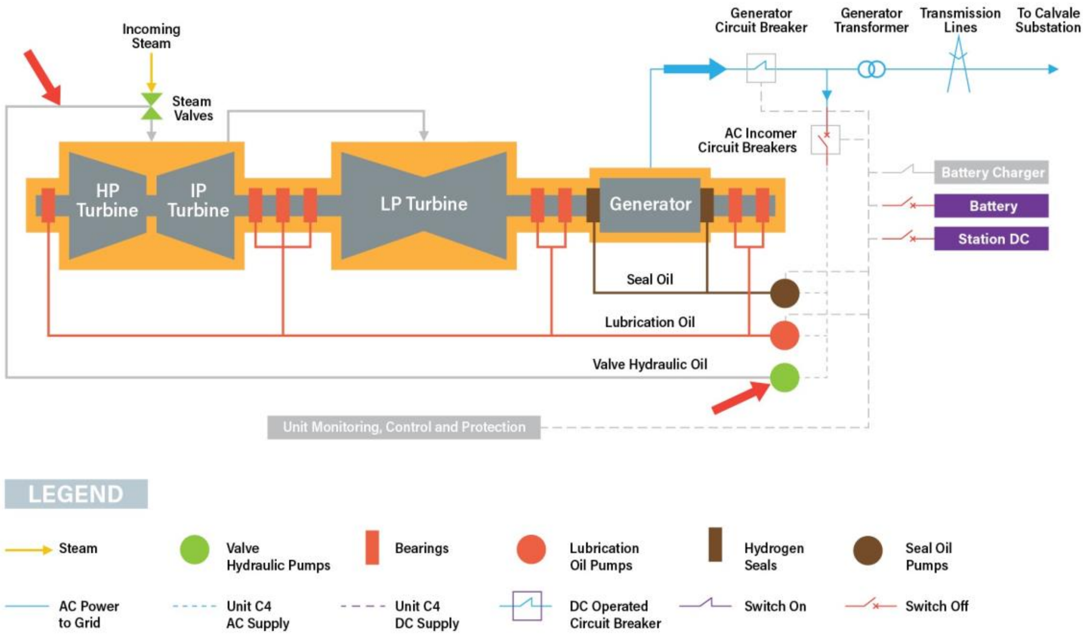


Figure 27 Loss of AC supply to the steam valve hydraulics

Second, the loss of AC supply led to the loss of the AC lubrication oil pumps, see Figure 28.

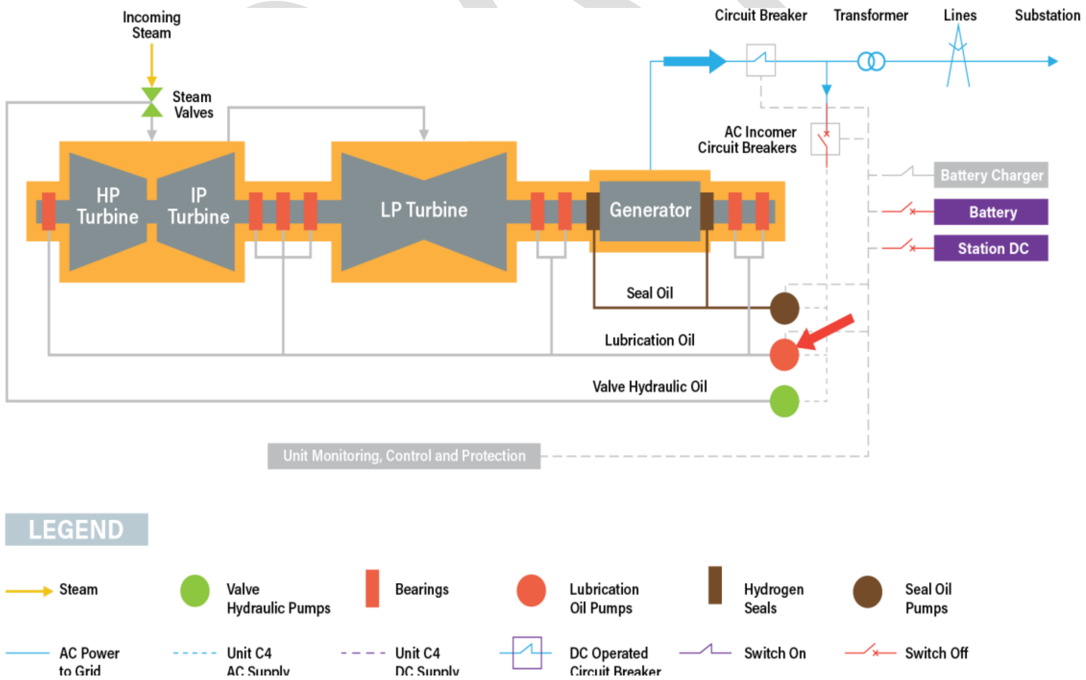


Figure 28 Loss of AC lubrication oil pumps

Oil supply to the bearings was lost. Ordinarily, the DC emergency lubrication oil pump would automatically start and restore lubrication oil to the bearings, but it did not operate because of the loss of its DC supply. This resulted in the shaft and bearings grinding metal-on-metal.[41]

Third, the loss of AC supply resulted in the loss of the AC seal oil pump to the generator, see Figure 29.

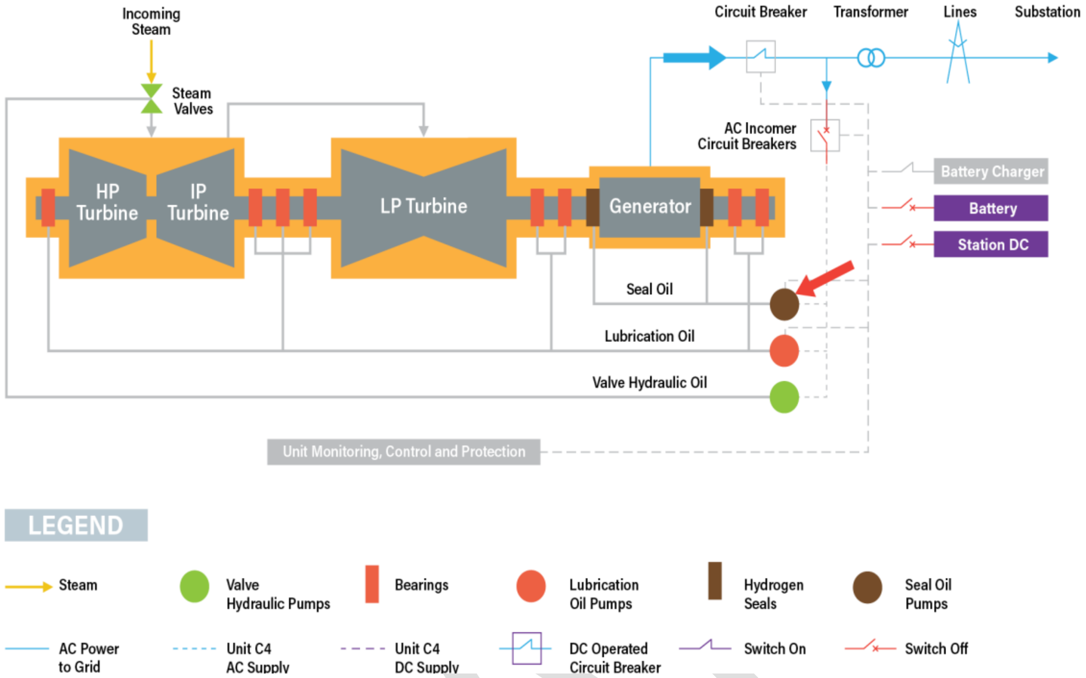


Figure 29 Loss of AC seal oil pump

Oil supply to the hydrogen seals was lost. Ordinarily, as above, the DC emergency seal oil pump would automatically start and restore oil to the hydrogen seals, but these did not operate because of the loss of their DC supply. This resulted in hydrogen escaping from the generator into the surrounding air.

Fourth, the loss of AC supply meant that none of the cooling systems critical for the safe operation of the turbine generator and generator transformer were available (not shown in the figure above).

Fifth, the loss of AC supply directly led to the loss of DC supply to Unit C4. While the DC system had already collapsed to ~120 V, it was the loss of AC that turned this collapse into a complete loss (~0 V). The Unit C4 battery charger requires AC supply in order to operate, and when AC supply was lost, the battery charger shut down. Since the battery charger was the sole source of DC supply to Unit C4, this led to the system voltage collapse (~120 V) turning into a complete loss (~0 V). Conversely, if the AC supply to the Unit C4 battery charger had not been lost, then it is likely that the battery charger would have responded to the DC voltage collapse and restored it to ~243 V within the order of ~2 seconds.

[41] The load on the Unit C4 turbine gradually increased from ~5 MW, reaching a peak of 80 MW after about seven minutes. It then settled at 50 MW until the turbine missile event occurred. Bearing temperatures rapidly increased (such as No. 2 bearing reaching melting point in ~100 seconds). It is hypothesised that after seven minutes, all white metal was likely melted away on the bearings, and this molten metal likely provided the 'lubrication' until the turbine missile event occurred, hence the reduction to approximately 50 MW until the turbine missile event. See Appendix A2 Mechanical Plant Events for further details.

4.5 Emergency Diesel Generator Failed to Restore Unit C4 AC Supply

When AC supply was lost, the emergency diesel generator should operate automatically and restore AC supply. On the day of the incident, it did operate, but AC supply was not restored to Unit C4.

AC supply was not restored because the AC system needs to be configured to receive this supply i.e., specific switches on the system need to be opened or closed. These switches are operated by the DC system, but because of the loss of DC supply, the necessary configuration could not be achieved. The AC supply from the emergency diesel generator could not be routed to the Unit C4 AC system.

4.6 Motoring Commenced

4.6.1 Introduction

The loss of AC and DC supply to Unit C4 created a situation where the unit commenced motoring. Two conditions were necessary for this to occur: the steam valves closed,[42] and the unit remained connected to the grid.

4.6.2 Steam Valves Closed

The loss of AC supply led to the failure of the hydraulic pumps, which provide hydraulic pressure to keep the steam valves open. As a result, the steam valves closed (due to their fail-safe design), thus preventing steam from entering the turbine, see Figure 30.

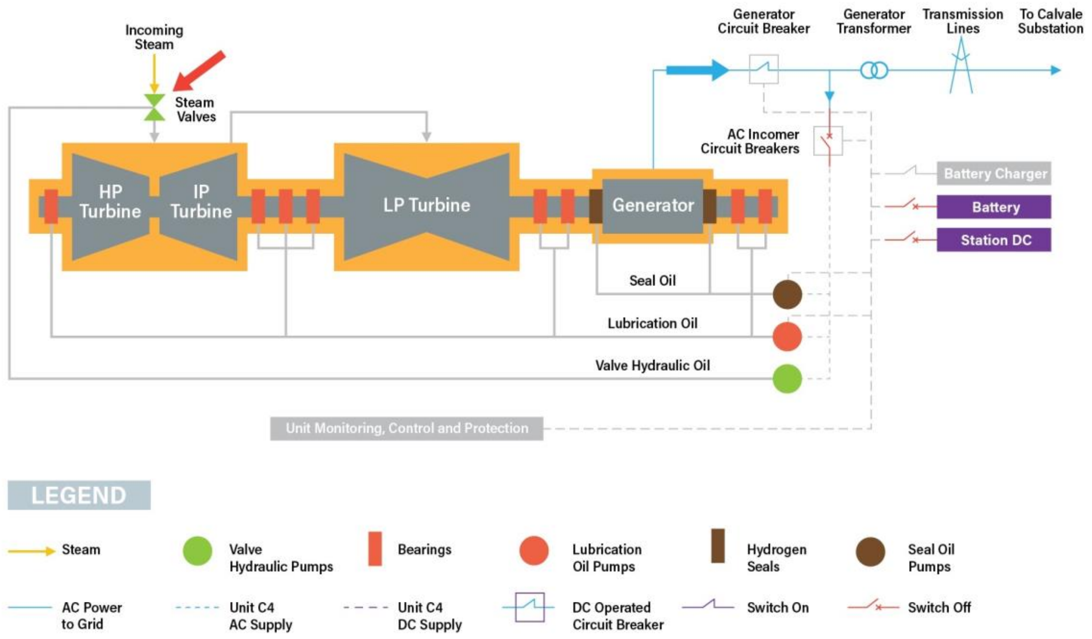


Figure 30 Steam valves close and prevent steam entering

[42] Specifically, it is a lack of steam driving the turbine that is a necessary condition. In the incident, it was the steam valves closing that resulted in a lack of steam driving the turbine.

4.6.3 Generator Circuit Breaker Did Not Disconnect Unit C4 from the Grid

A loss of AC supply would typically be detected by the Unit C4 protection systems.[43] This would automatically trip the generator circuit breaker, disconnecting the unit from the grid. However, the loss of DC supply meant that Unit C4's protection systems were no longer functioning, nor was there DC supply available to open the generator circuit breaker, see Figure 31.

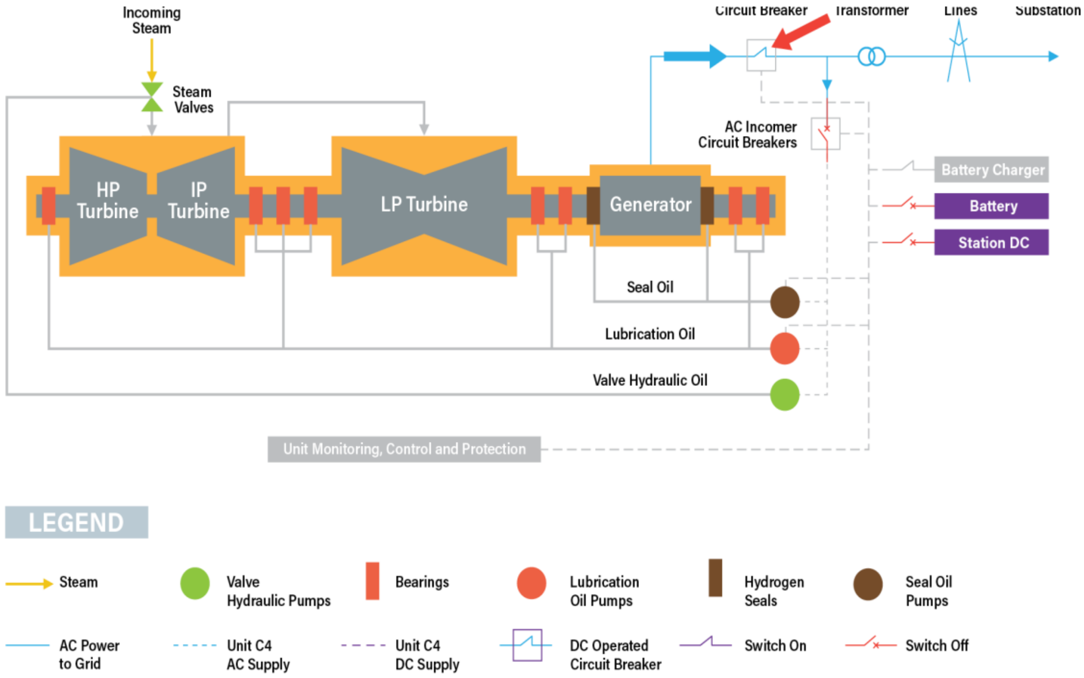


Figure 31 Generator circuit breaker did not disconnect Unit C4 from the grid

Because the generator circuit breaker did not operate, Unit C4 remained connected to the grid for the duration of the incident.

4.6.4 Unit C4 Commenced Motoring

Because Unit C4 was still connected to the grid, with no steam driving the turbine, Unit C4 began 'motoring'. Motoring in a turbine generator is when it stops exporting power to the grid, and instead imports power and becomes an electric motor, continuing to spin (in the same direction) at a slightly slower speed than 3,000 rpm, see Figure 32.[44]

[43] 'Typically' means that the Unit C4 protection systems need their DC supply available in order to function and detect a loss of AC supply.

[44] While the turbine generator typically rotates at 3,000 rpm when exporting power, it rotates at a slightly slower speed when motoring asynchronously.

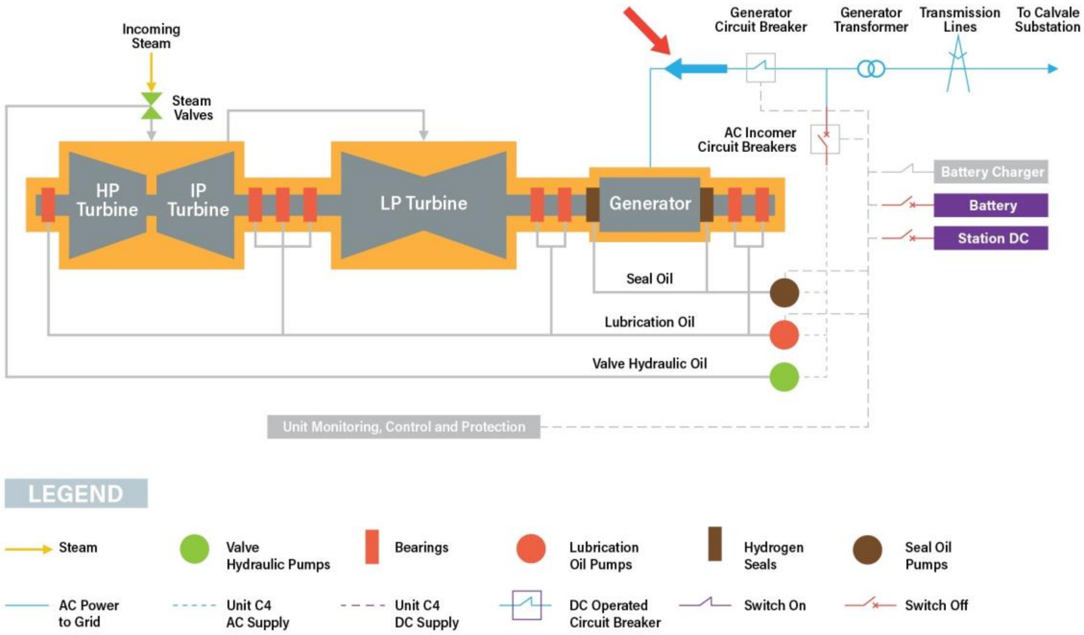


Figure 32 Motoring commences

4.7 Calvale Substation Circuit Breaker Did Not Open Automatically

If the generator circuit breaker on a unit is unable to open for any reason, the unit's protection systems typically send a signal to Calvale substation. The circuit breaker (associated with that unit) at Calvale substation opens on receipt of the signal, disconnecting the unit from the grid.

This did not occur in the incident. As discussed above, the generator circuit breaker did not open, but because of the loss of Unit C4 DC supply, the Unit C4 protection systems had no ability to communicate with Calvale substation to open its circuit breaker. There was no automatic disconnection of Unit C4 from the grid and it continued to motor.[45]

In this state, the only remaining mechanism available to disconnect Unit C4 from the grid (and stop the motoring) was for the circuit breaker at Calvale substation to be the manually operated by Powerlink. This would have required Unit C4 operators to understand the situation unfolding at Unit C4, and communicate such a request to Powerlink.

4.8 Loss of Supply to Unit C4 Operator Screens in Control Room

All four units at Callide are operated from a single control room located in the turbine hall building.[46] The operators in the control room rely on several display screens to monitor the status of the plant and to control equipment.

[45] While the systems at Calvale substation detected the loss of signal from Callide C, it did not receive a positive 'request for opening breaker' message.

[46] There is a single control room for all four units (B1, B2, C3 and C4) of the Callide B and Callide C power stations. Unit C4 is located some distance away from the control room.

When the incident began, the loss of both AC and DC supply resulted in the display screens for Unit C4 powering off (going black).[47] Supply to these screens was restored by the operators after approximately 20 minutes, which is will discussed further in Chapter 13.

4.9 34 Minutes of Sustained Motoring

Unit C4 was now operating without protection (due to the loss of DC supply). It had lost both its main and emergency lubrication and seal oil pumps (due to the loss of AC supply and DC supply, respectively).[48] The steam valves were closed (due to the loss of AC supply).

With no oil to the bearings, the white metal lining of the bearings melted in a few minutes and led to metal-on-metal contact between the rotor journals and bearings. Heat caused by friction caused the bearings to melt and the rotor to soften and deform. This deformation caused the turbine generator rotor to wobble on its axis.

With no seal oil to keep the pressurised hydrogen gas inside the generator, the hydrogen leaked out through the seals and likely combusted in the air.[49]

With no steam to drive the turbine, the Unit C4 generator acted like an electric motor. This motoring continued for 34 minutes without any operational cooling systems for the turbine generator or the generator transformer.[50]

4.10 Catastrophic Failure

At 2:06 pm, the shaft, which was still rotating close to 3000 rpm, tore apart in nine locations. This is referred to as the 'turbine missile event', and it was likely due to excessive wear in the shaft causing the turbine blades to catch on the casing. A piece of shaft weighing more than two tonnes was thrown five metres across the floor. A piece of equipment known as the 'barring gear' (weighing 300 kg) was ejected 20 metres into the air, punching through the turbine hall roof.

The event also ejected remnants and debris of coupling covers, bearings, and sections of the shaft at significant force, resulting in widespread damage to the surrounding environment, including the floor, wall and roof of the turbine hall, see Figure 33.

[47] The control room display screens are powered via a UPS with both an AC supply and a DC supply to provide redundancy in the event of one supply being lost. If only one supply had failed, there would not have been a loss of screens.

[48] Unit C4 has two AC lubrication oil pumps and one emergency DC lubrication oil pump, and one AC seal oil pump and one emergency DC seal oil pump. The valve hydraulics, stator coolant, treated cooling water, auxiliary cooling water and main cooling water systems only have AC pumps.

[49] It is likely to have caused a small explosion in the main oil tank of Unit C4.

[50] The turbine generator was motoring at around 50 MW and 300 MVAR, without cooling systems, which include main cooling water, treated and auxiliary cooling water, stator cooling and transformer cooling – all of which are usually supplied by the Unit C4 AC system.

Figure 33 Damage to Unit C4

4.11 Unit C4 Disconnection from the Grid

The generator remained connected to the grid for approximately 40 seconds after the turbine missile event. During this time, an electrical fault developed in the generator, which caused it to draw large current from the grid – the resulting import was nearly three times the unit's rated export power.[51]

The protection systems at Calvale substation detected the fault and disconnected the substation from the grid. This in turn disconnected Unit C4 from the grid.[52]

By this time, 2:06 pm, the generator and generator transformer had been destroyed, and the disconnection of Calvale substation had initiated the destabilisation of the Queensland power grid.

[51] The imported power from the grid peaked at 300 MW and over 1400 MVAR.

[52] AEMO (2021) *Trip of multiple generators and lines in Central Queensland and associated under-frequency load shedding on 25 May 2021*. https://www.aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2021/trip-of-multiple-generators-and-lines-in-qld-and-associated-under-frequency-load-shedding.pdf Section 4.1: '*The Callide C4 fault which occurred at 14:06 hrs was picked up by protection on circuits connecting Calvale to the wider network in protection zone 2, this was detected as a phase A – B – ground fault. … The protection operation opened all remote end circuit breakers connecting Calvale 275 kV substation to the wider system, disconnecting Callide C4 from the power system. The overall time from fault inception to clearance was approximately 600 ms*.'

4.12 Overview of Damage

The following series of photographs show the extent of the damage that occurred during the incident. Figure 34 shows the overall damage to the turbine generator from the east side.

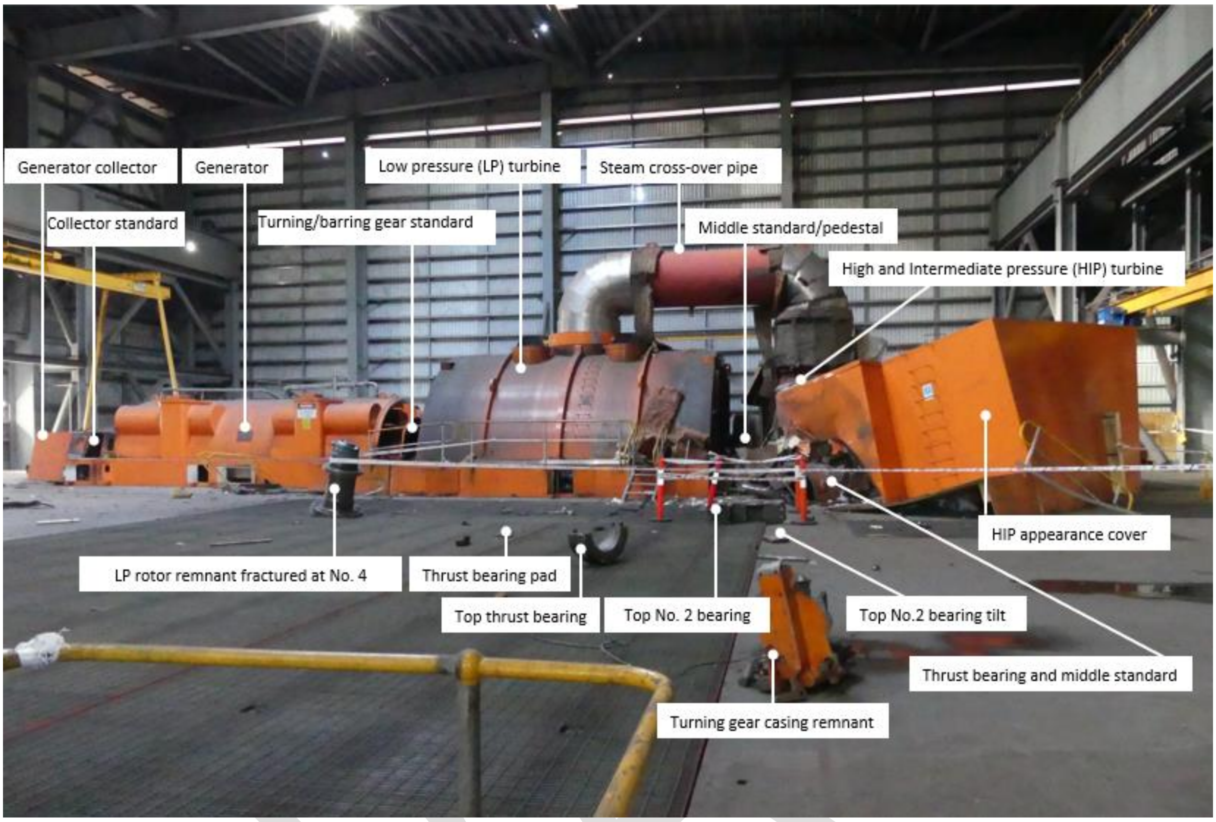


Figure 34 Damage to Unit C4 (east side view)

Figure 35 shows the aerial view of damage to the Unit C4 turbine generator.

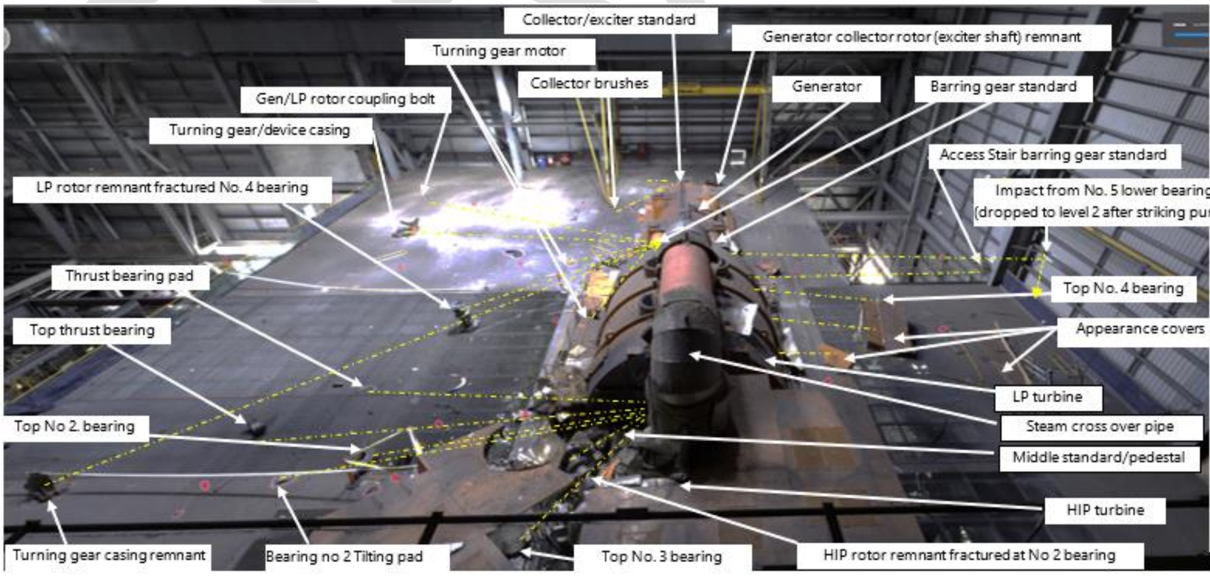


Figure 35 Damage to Unit C4 (aerial view)

Figure 36 shows the damage between the generator and LP turbine.

Figure 36 Damage between the generator and LP turbine

Figure 37 shows the area between the LP and HIP turbine.

Figure 37 Damage between LP and HIP turbines

Figure 38 shows a selection of photographs of remnants of the shaft.

Figure 38 HP turbine, LP turbine and generator shaft damage

Figure 39 shows the heat damage to the casing for the LP turbine.

Figure 39 Heat damage to LP turbine casing

Figure 40 shows the damage to the generator stator.

(a) Generator stator internal condition

(b) Damage to stator bars

Figure 40 Damage to the generator stator

4.13 Cause of the Incident

The damage to Unit C4 was the result of the loss of both DC and AC supply to the unit.

4.14 Causes of Incident Ruled Out

Causes of failure ruled out as part of the investigation are briefly discussed below, with further discussion provided in Appendix XX and XX.

4.14.1 Overspeed Event

A well-understood catastrophic failure mechanism in turbine generators is an 'overspeed event'. In normal operation, when the turbine generator is connected to the grid and generating electricity, the rotation of the generator rotor is resisted by the grid. If the generator is disconnected from the grid (for example, by opening the generator circuit breaker), this resistance is removed. If this resistance is removed while the turbine is still being driven by steam, the turbine generator rapidly speeds up – due to the loss of resistance - and can tear itself apart in the order of 10 seconds.

The damage to Unit C4 was highly unlikely to have been caused by an overspeed event because:

- There was no steam driving the turbine throughout the 34 minutes of motoring to cause an overspeed event.
- The turbine generator remained connected to the grid throughout the duration of the incident, limiting the speed of rotation to approximately 3,000 rpm.

4.14.2 Mechanical or Metallurgical

Mechanical or metallurgical failures are highly unlikely to have contributed to the cause of the incident.

4.14.3 Cybersecurity

A digital fault or cyber-attack (whether internal or external) is highly unlikely to have contributed to the cause of the incident.

4.15 Chapter Summary

The collapse, loss, and failure to recover the AC and DC systems on Unit C4 resulted in the catastrophic failure of the unit.

The following chapters of this report examine in more detail how the collapse, loss, and failure to recover the AC and DC systems to Unit C4 occurred, namely:

- Chapter 5 The Callide C Electrical System provides a more detailed overview of the Unit C4 AC system and DC system (within the Callide C electrical system).
- Chapter 6 The Role of the Switching Sequence in the Incident examines the switching sequence that was taking place on the Callide C electrical systems on the day of the incident.
- Chapter 7 The Role of the Electrical System in the Incident discusses how the loss of supply to the Unit C4 DC and AC systems led to the incident.
- Chapter 8 How the Loss of AC Occurred explains how the loss of DC supply led to the loss of AC supply.
- Chapter 9 The Role of the Unit C4 Battery Charger in the Incident examines how the behaviour of the Unit C4 battery charger led to the loss of DC supply to Unit C4.

5 THE CALLIDE C ELECTRICAL SYSTEM

5.1 Introduction

While Chapter 3 provided a simplified overview of Callide C electrical system, this chapter provides a more detailed discussion of its two key components: the AC system and the DC system.

It explains the components and typical configuration of both systems, then shows how these systems integrate with the wider Callide C electrical system. Some repetition of material already presented is necessary.

As discussed in Chapter 4, the cause of the incident was due to the loss of both DC and AC supply to Unit C4.

5.2 Callide C Electrical System

Figure 41 shows a simplified representation of the Callide C electrical system. The AC system is shown at the top of the figure, with the DC system at the bottom. Both systems will be explained in the sections that follow.

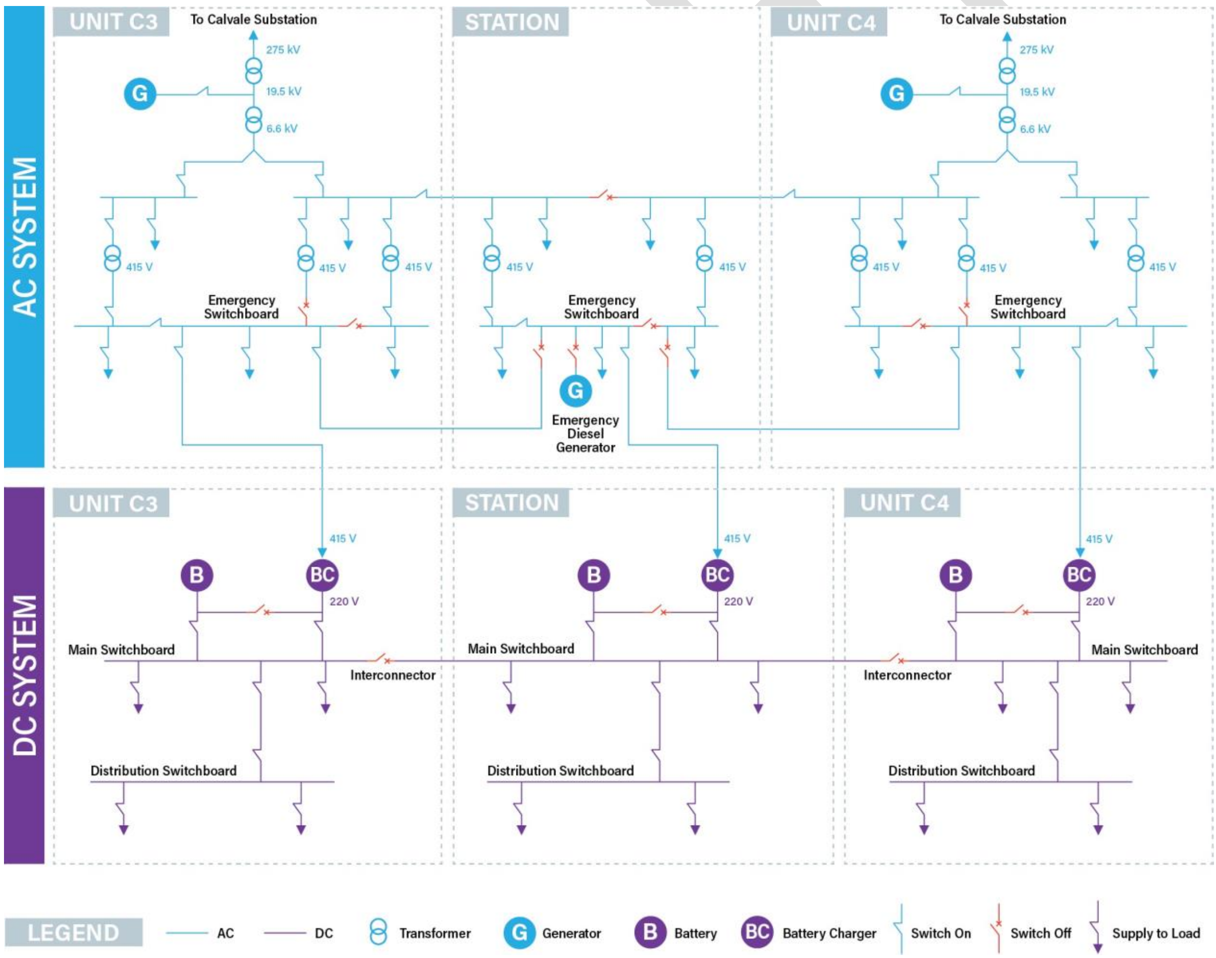


Figure 41 Callide C AC and DC systems

The AC system supplies the majority of equipment at Callide C, e.g., it drives the large motors on pumps and fans. AC is a readily available source of supply from the grid and can be converted to different voltage levels through transformers.

The DC system is separate to the AC system and it supplies equipment that protects, monitors and controls the operation of each unit. It also supplies backup equipment, such as emergency lubrication oil pumps and emergency seal oil pumps. DC is used for this application primarily because it can be stored in a battery, meaning that if AC supply is lost, DC supply will be available to facilitate the safe shutdown of the unit.

There are interactions between these two systems, which will be discussed later in this report.

5.3 Introduction to the Unit C4 AC System

This section explains the AC system at the Callide C power station, focusing first on the Unit C4 AC system, see Figure 42.

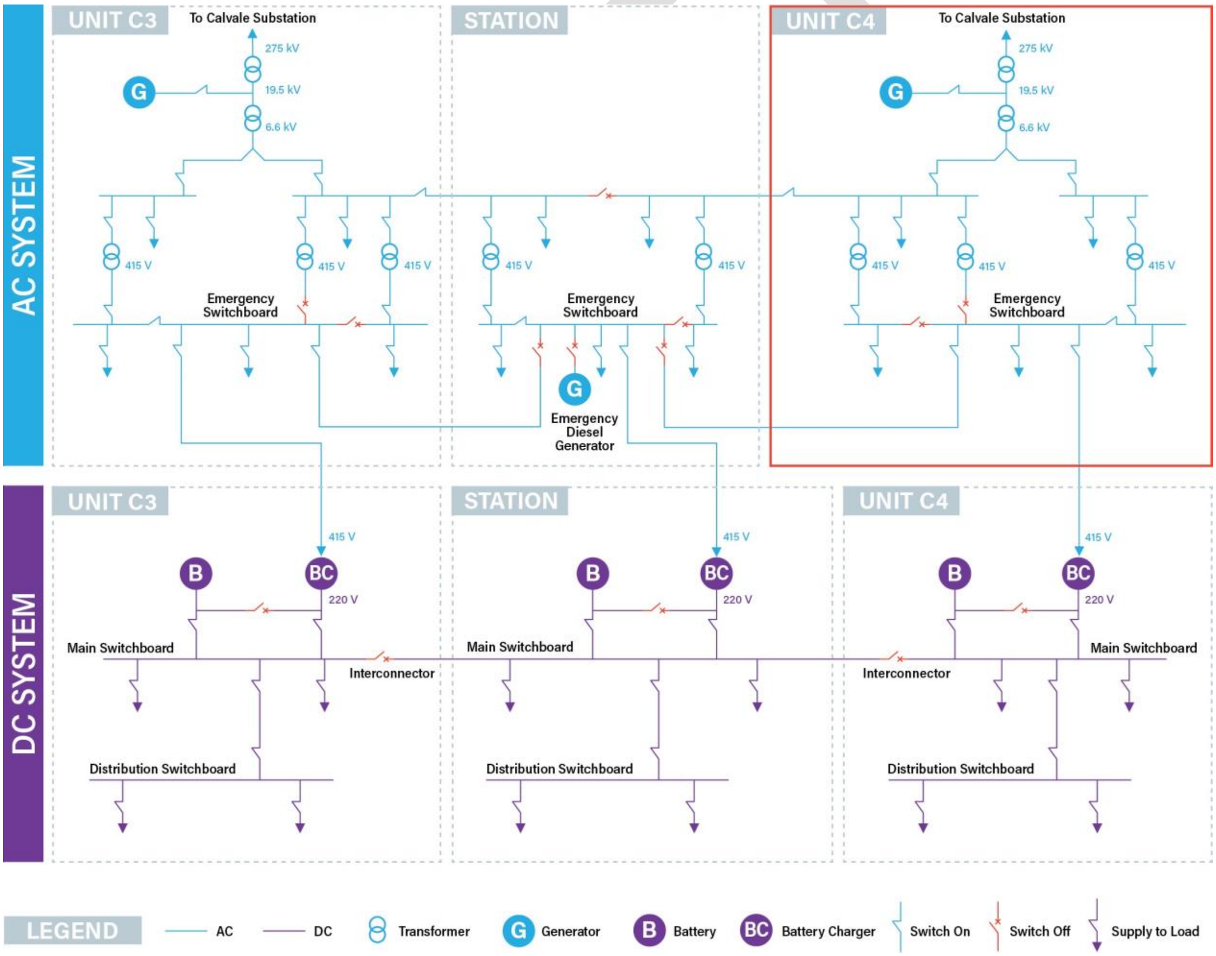


Figure 42 Unit C4 AC system (indicated in red)

5.3.1 Generator

Unit C4 generates AC electricity at 19.5 kV. Figure 43 shows Unit C3, to illustrate the condition of Unit C4 prior to the incident.

Figure 43 Unit C3 generator (identical to Unit C4)

5.3.2 Generator Circuit Breaker and Generator Transformer

Electricity generated by Unit C4 is exported to the grid via the generator circuit breaker and the generator transformer. Figure 44 shows the Unit C3 generator circuit breaker, which is identical to Unit C4.

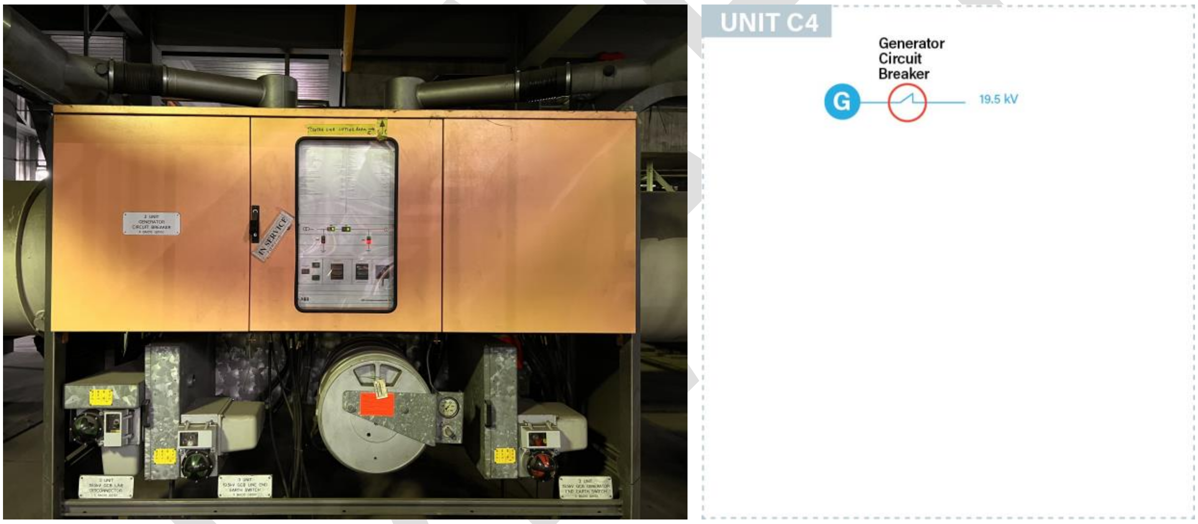


Figure 44 Unit C3 generator circuit breaker (identical to Unit C4)

The role of the generator circuit breaker is to both connect and disconnect the generator from the grid.

Figure 45 shows the Unit C3 generator transformer (which is the same as the Unit C4 generator transformer), located outside the turbine hall building.

Figure 45 Unit C3 generator transformer (identical to Unit C4)

The role of the generator transformer is to convert electricity produced by the generator from 19.5 kV to 275 kV, which is the transmission grid voltage. The fans that cool the generator transformer can be seen in the foreground of the figure above.

5.3.3 Calvale Substation

The electricity supply generated from Unit C4 passes through overhead cables at 275 kV to Calvale substation, which is operated by Powerlink, see Figure 46.

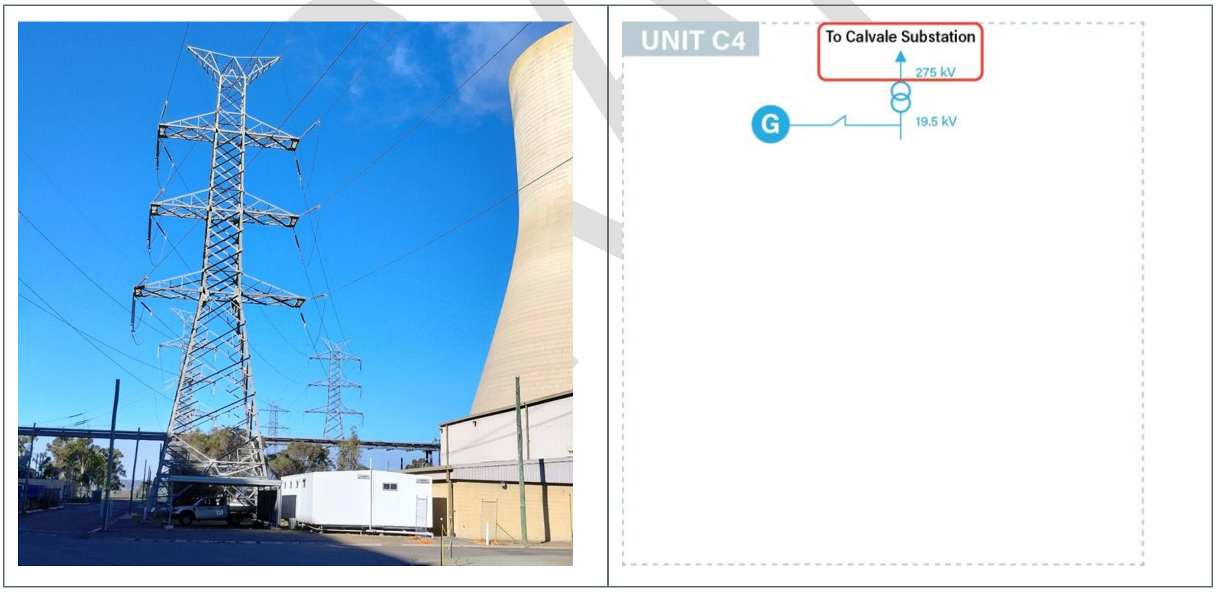


Figure 46 Transmission lines from Unit C4 to Calvale substation (circled in red)

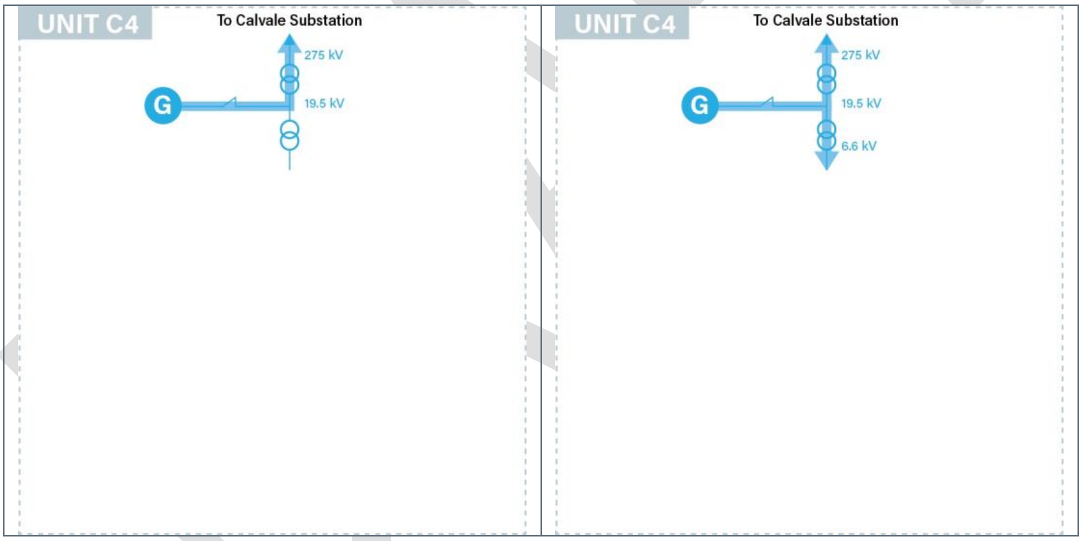
5.3.4 Step-Down Transformer

The 19.5 kV supply from the generator is passed through another transformer that steps down the voltage to 6.6 kV. This 6.6 kV voltage supplies the Unit C4 AC system. Figure 47 shows the Unit C3 step-down transformer, which is the same as in Unit C4.

Figure 47 Step-down transformer (circled in red)

5.3.5 Importing and Exporting AC Power

When the generator is operating normally, the electricity it produces is exported to Calvale substation. It is also used to supply the Unit C4 electrical system, see Figure 48.



(a) *Generator exports to Calvale substation*

(b) *Generator also supplies Unit C4*

Figure 48 Unit C4: exporting to Calvale substation and supplying Unit C4 AC system

5.3.6 6.6 kV Incomer Circuit Breakers

The 6.6 kV AC supply to Unit C4 is via two 6.6 kV incomer circuit breakers. Figure 49 shows a 6.6 kV circuit breaker at Unit C4.

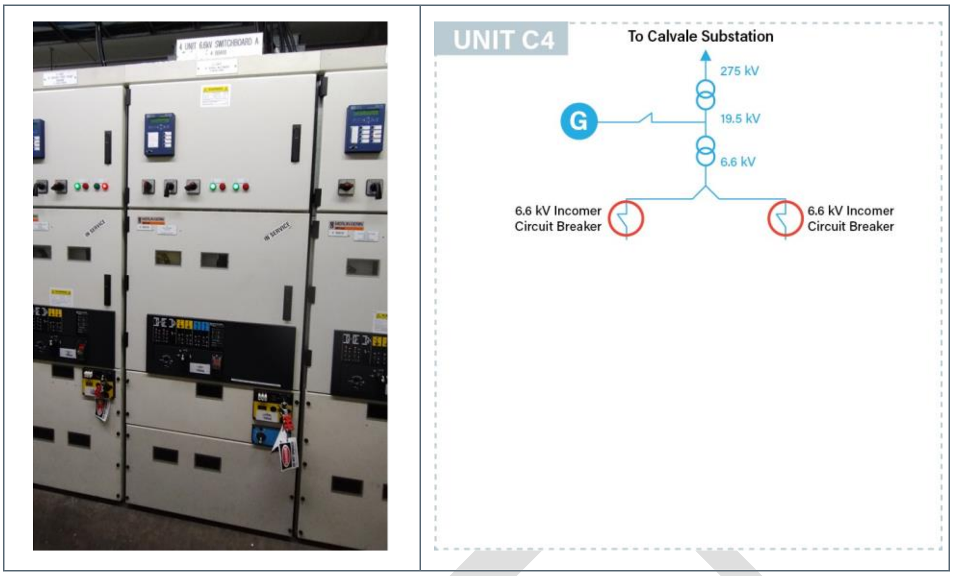


Figure 49 AC 6.6 kV incomer circuit breakers (circled in red)

The purpose of the AC incomer circuit breakers is to connect and disconnect the AC supply to the unit.

5.3.7 Switchboards

The AC supply is then distributed to two 6.6 kV switchboards, where it is supplied to large equipment, see Figure 50.[53,54]

[53] In this report, for simplicity, various circuit breakers and switchgear have been referred to as 'switches'.

[54] Electrical equipment connected to a switchboard is referred to as a 'load'.

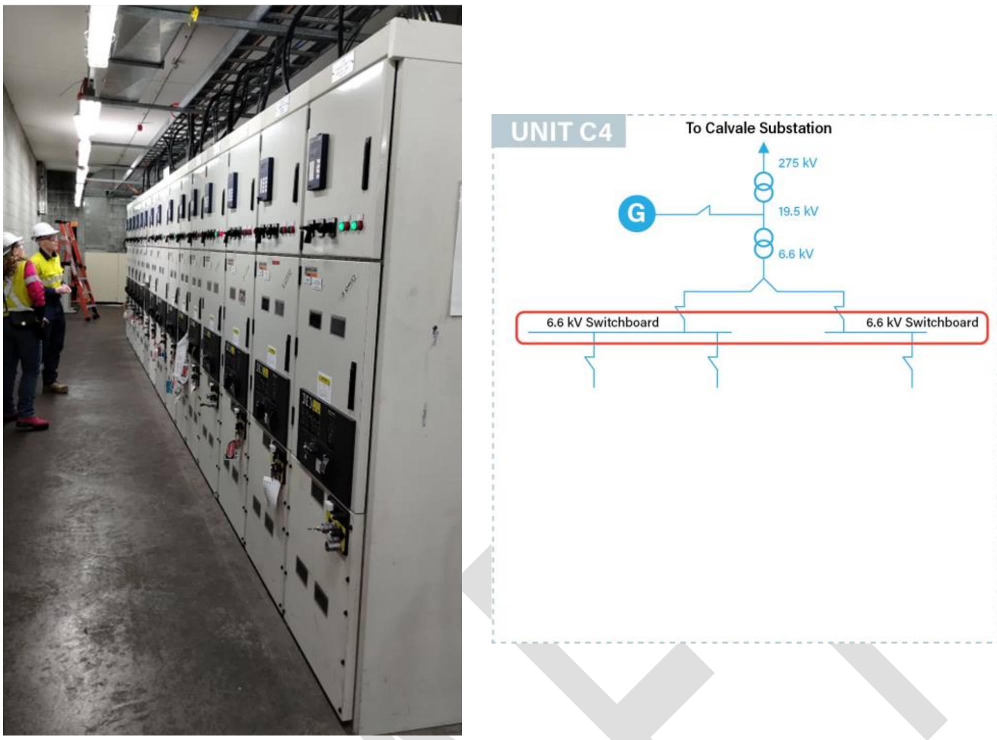


Figure 50 6.6 kV AC switchboards (circled in red)

5.3.8 Transformers

The 6.6 kV supply connects to a number of transformers, which step the voltage down to 415 V, see Figure 51.

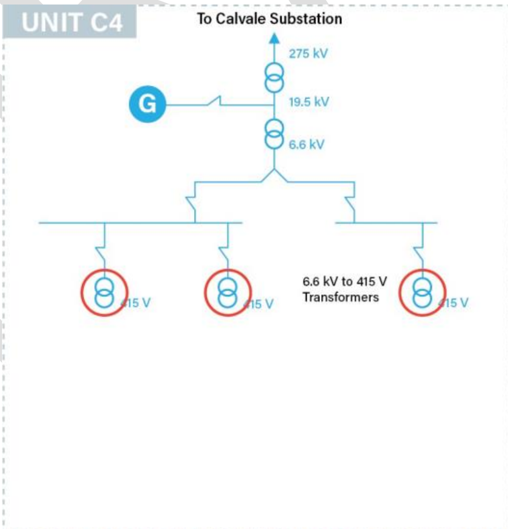


Figure 51 Transformers (circled in red)

The 415 V AC is used to supply various small loads, such as motors, fans, valves, pumps, lighting, power outlets, and air conditioning.

5.3.9 415 V Emergency Switchboard

The 415 V AC supply connects to an emergency switchboard, which supplies equipment critical for the safe operation of Unit C4, see Figure 52. The emergency switchboard is continuously powered,

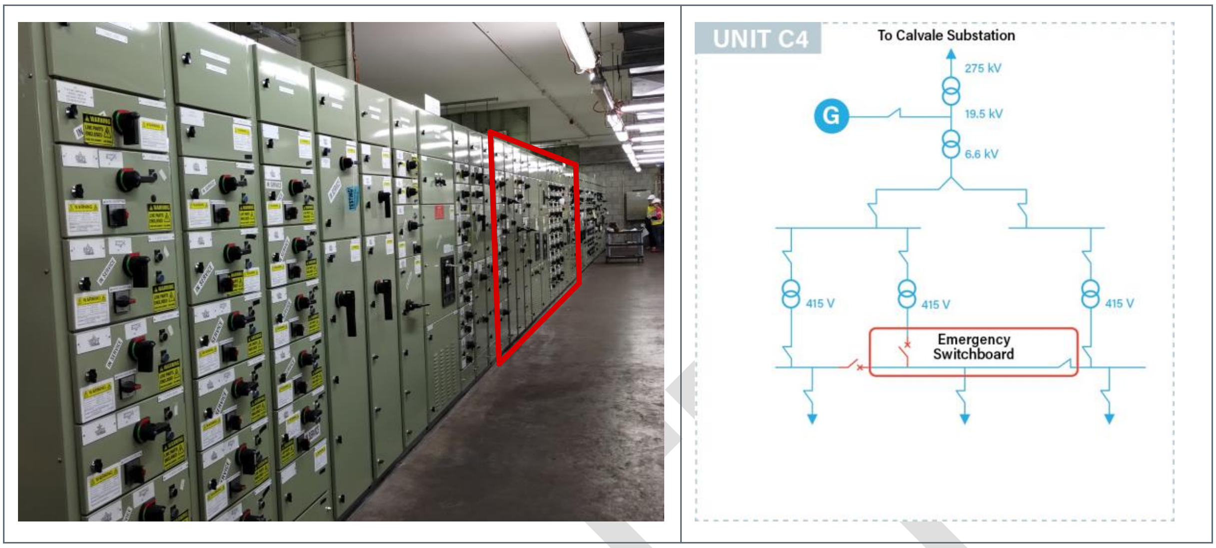


Figure 52 Unit C4 415 V AC switchboards (with emergency switchboard indicated in red)

This emergency switchboard provides supply to essential loads, such as the main lubrication oil pumps and the battery charger (discussed below).[55]

5.4 Introduction to the Callide C AC System

5.4.1 Unit C3 and Station AC Systems

In addition to the Unit C4 AC system, there is a Unit C3 AC system and a Station AC system. The Unit C3 AC system is identical to Unit C4, see Figure 53.

[55] While the emergency switchboard is the primary 415 V switchboard focused on in this report, there are multiple 415 V AC switchboards, including a single phase (240 V AC) switchboard provided via a UPS/inverter.

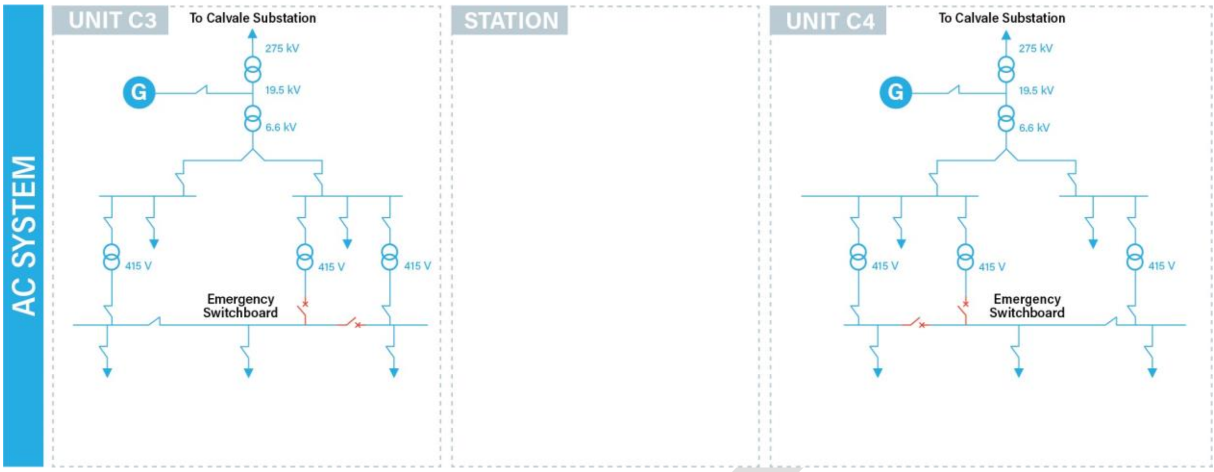


Figure 53 Unit C3 and Unit C4 AC systems

The Station AC system is located between the Unit C3 and Unit C4 AC systems. It has its own 6.6 kV to 415 V transformers, and its own 415 V emergency switchboard, see Figure 54.

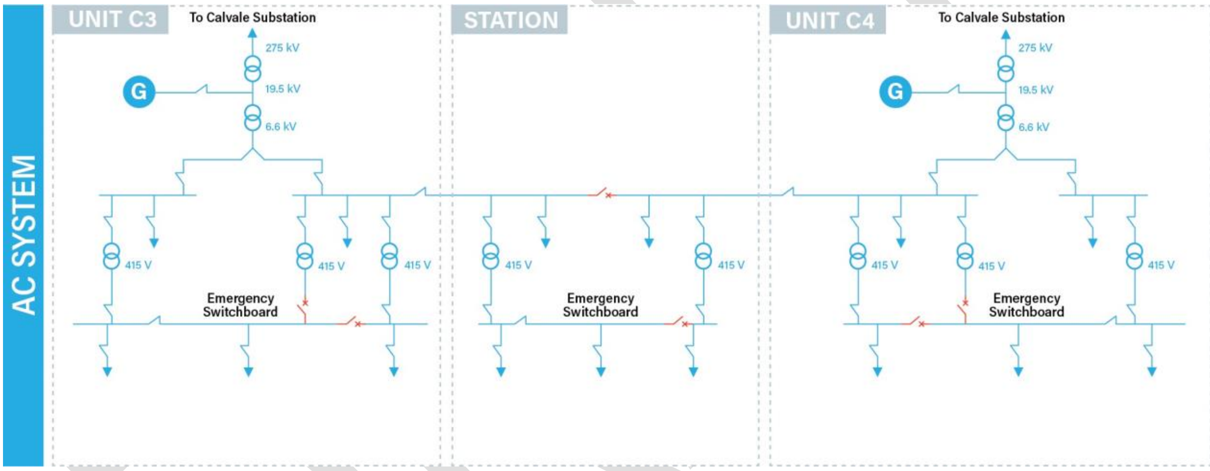


Figure 54 Unit C3, Unit C4 and Station AC systems

Station does not have a turbine generator (nor its own 275 kV to 6.6 kV transformer) to provide AC supply. Instead, it receives supply from either Unit C3 or Unit C4. Figure 57 illustrates Unit C3 supplying part of the Station system.

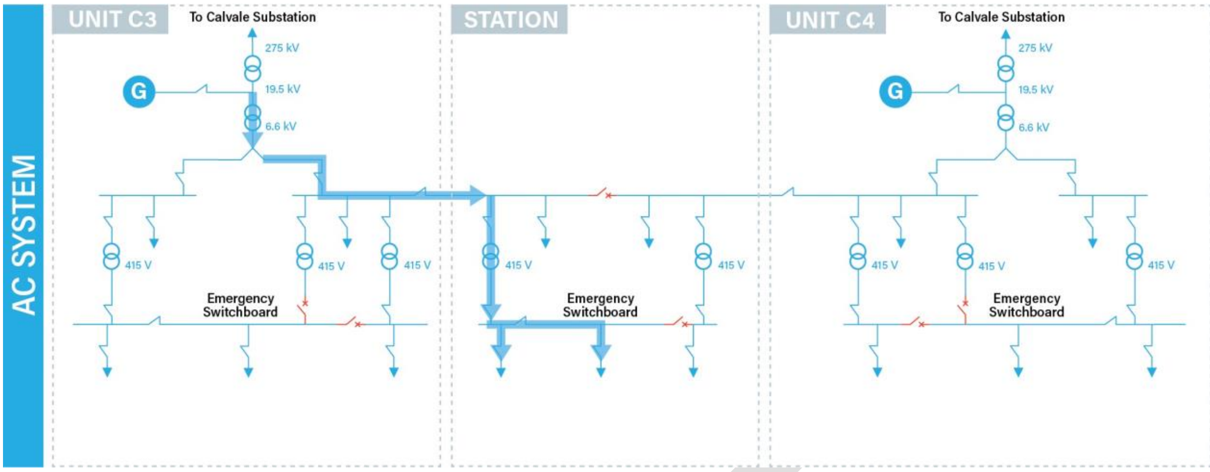


Figure 55 Station receiving AC supply from Unit C3

The 415 V emergency switchboards supply key AC equipment and systems. These switchboards are all interconnected via switches, which give the ability to configure the system in a manner that allows the distribution of AC supply to specific switchboards. Figure 56 shows the interconnection between the Unit C3, Station and Unit C4 emergency switchboards.

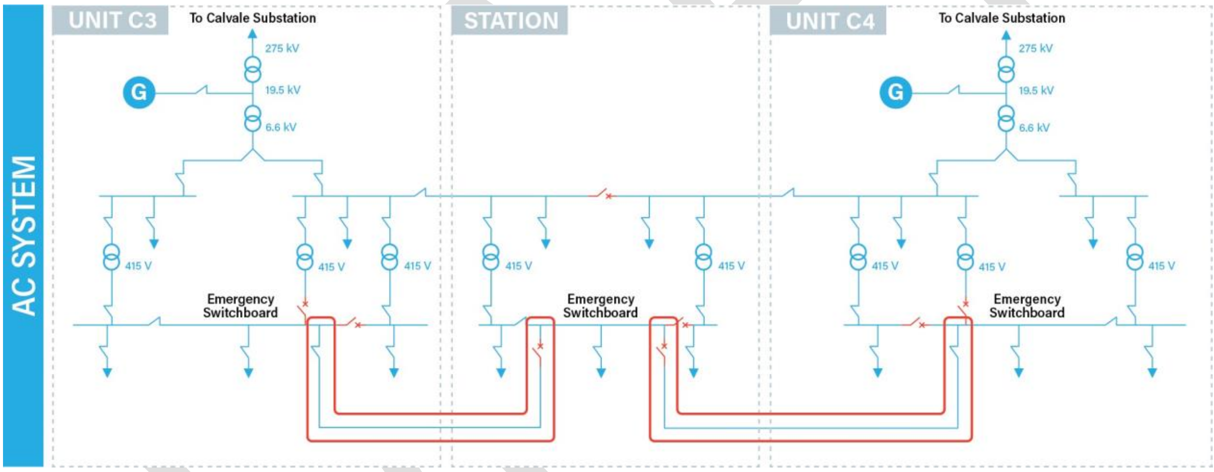


Figure 56 Interconnection between the Unit C3, Station and Unit C4 emergency switchboards

5.4.2 Emergency Diesel Generator

Figure 57 shows the emergency diesel generator at Callide C, which can provide AC supply to the Unit C3, Unit C4, and Station emergency switchboards in the event of a loss of AC supply.

Figure 57 Emergency diesel generator

If a loss of AC supply occurs, the emergency diesel generator will start automatically and connect to the Station emergency switchboard. The Station emergency switchboard can then be configured to supply the Unit C3 and Unit C4 emergency switchboards, via switches. Figure 58 illustrates how the Unit C4 emergency switchboard can receive AC supply directly from the Station emergency switchboard.

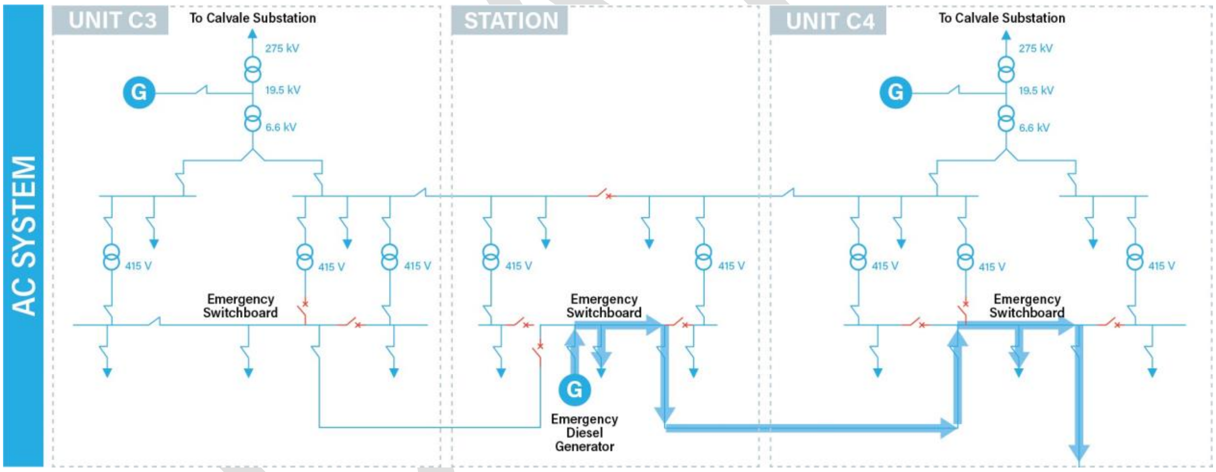


Figure 58 AC supply from emergency diesel generator to Unit C4 emergency switchboard via Station emergency switchboard

5.5 Introduction to the Unit C4 DC System

5.5.1 Overview of the DC System on Unit C4

The DC system on Unit C4 is identified in Figure 59.[56]

[56] Note that the DC system operates at a nominal voltage of 220 V. This nominal voltage is depicted in the figures in this report. The report text will provide the actual (or approximate) voltages of the DC system when relevant to the discussion.

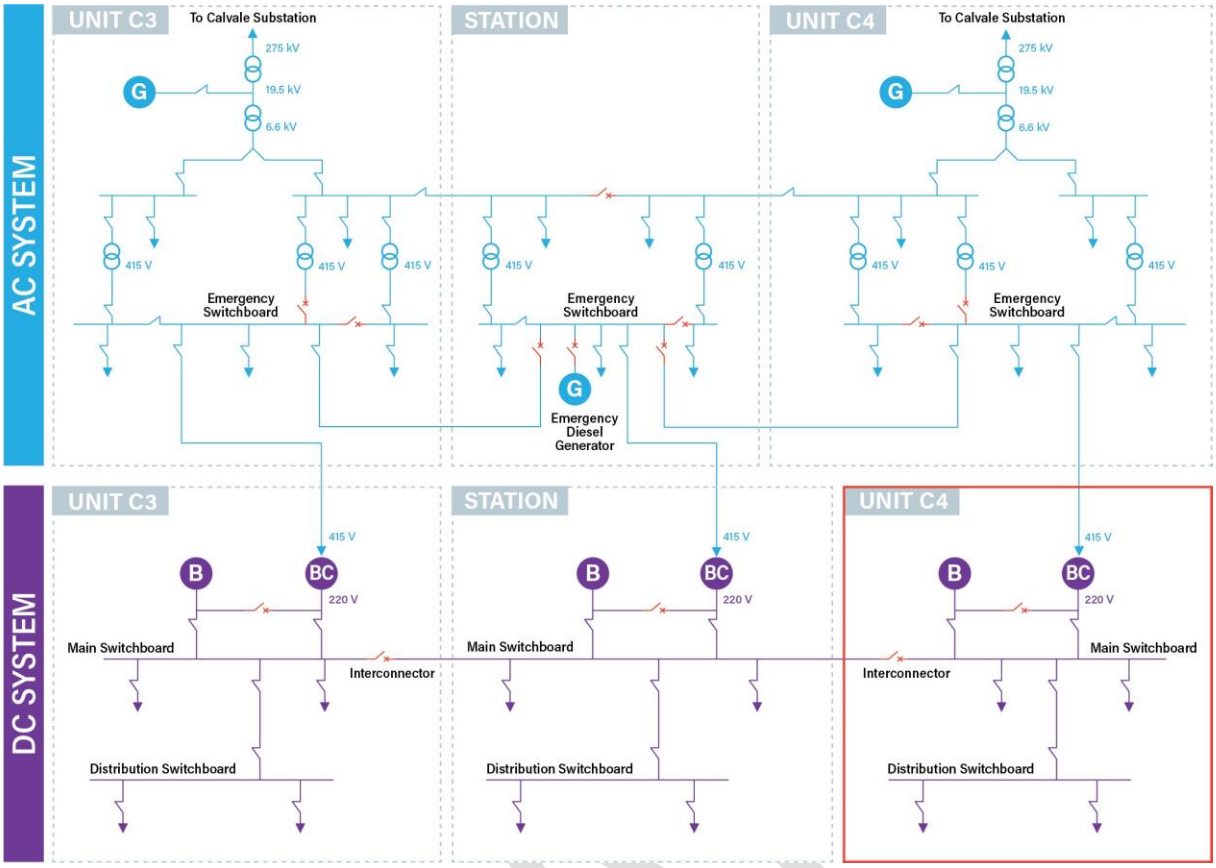


Figure 59 Unit C4 DC system (indicated in red)

5.5.2 Battery Charger and Battery

The Unit C4 DC system has two sources of supply: a battery charger and a battery. Figure 60 shows the Unit C4 battery charger.

Figure 60 Unit C4 battery charger

Figure 61 shows the Unit C4 battery.

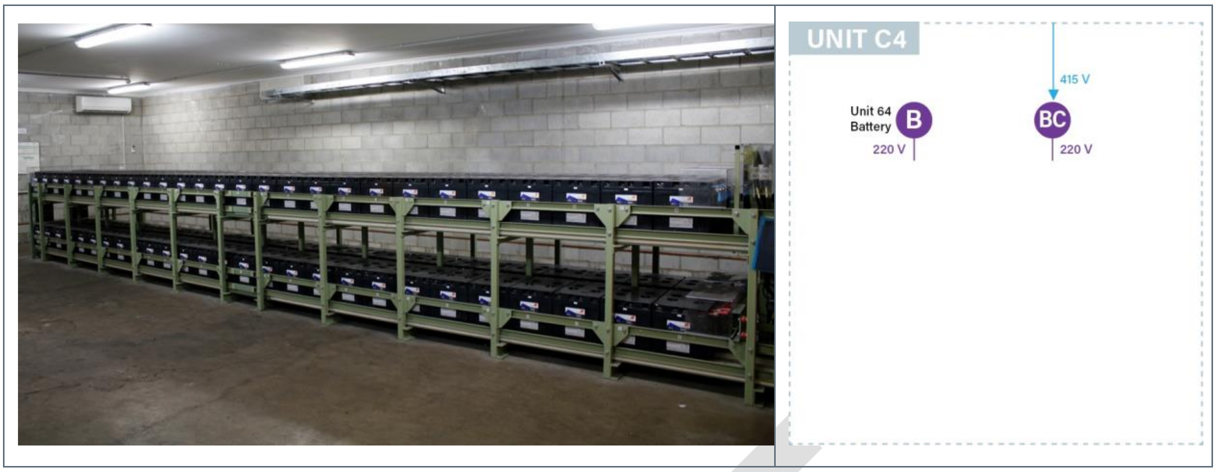


Figure 61 Unit C4 battery[57]

The relationship between the battery charger and battery is explored in more detail later in this chapter.

5.5.3 Main Switchboard

As shown in Figure 62, the Unit C4 battery charger and battery both connect to the Unit C4 main switchboard.

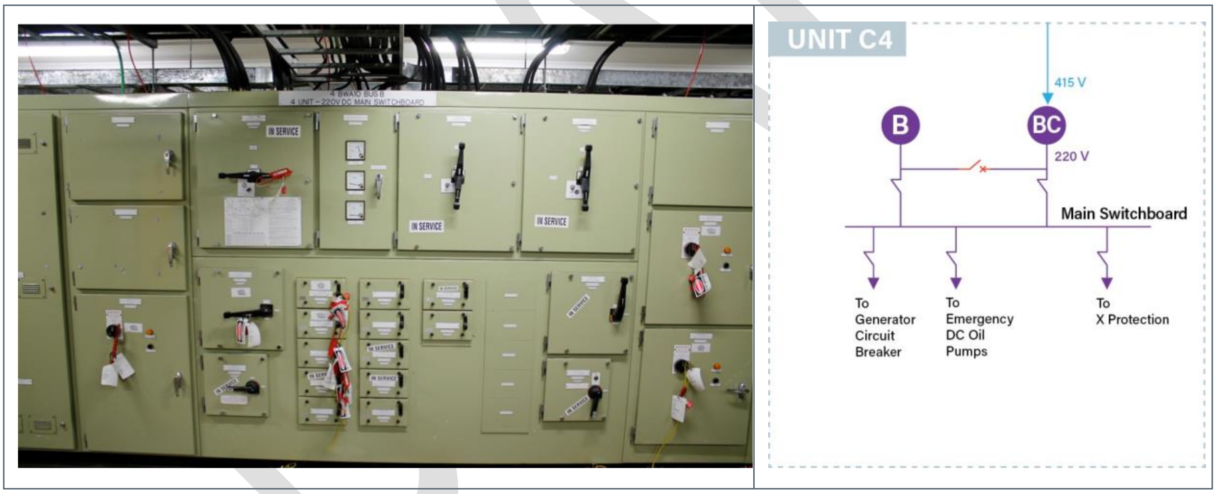


Figure 62 Unit C4 main switchboard

The main switchboard distributes DC supply to a range of systems, including the emergency DC lubrication oil and seal oil pumps. The main switchboard supplies power to the Unit C4 generator circuit breaker, allowing it to operate automatically or to be operated remotely from the control room, if necessary.

[57] Unit C4 battery consists of a string of 108 individual cells connected in series, which are collectively referred to as the Unit C4 battery.

The main switchboard also supplies part of the Unit C4 protection system known as the 'X protection system', which in simple terms monitors and protect the turbine generator.[58] When the X protection system detects a fault or issue, it takes appropriate action, such as safely shutting down the unit and disconnecting it from the grid (by operating the generator circuit breaker).

5.5.4 Relationship between Battery Charger and Battery

The battery charger and battery are both connected to the main switchboard via their own switches.[59] As discussed earlier, the battery charger primarily provides DC supply to the equipment in the DC system, while also keeping the battery at a full state of charge.[60] Therefore, the battery charger should be considered the primary source of supply to the DC system. Figure 63 illustrates this concept for Unit C4.

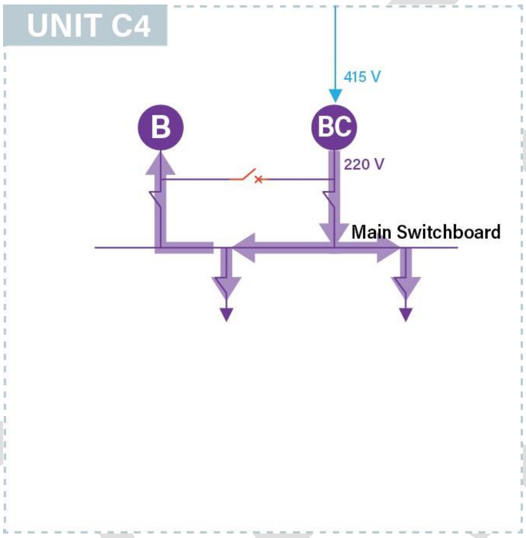


Figure 63 Battery charger supplying Unit C4

The battery plays an important operational role if the battery charger fails to operate, such as if it was disconnected from the DC system or its AC supply is lost. If this occurs, the battery takes over the role of providing DC supply to the system, thus providing important redundancy. Figure 64 represents this concept for Unit C4.

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[58] The X protection and Y protection (discussed in Section 5.5.5) monitor the generator, generator transformer, unit transformer and excitation system for electrical faults. The X and Y protection responds to trip signals from the turbine protection system and Calvale substation (which are separate from the X and Y protection systems). The X and Y protection can also send trip signals to the turbine and boiler in the event of an electrical fault on the generator, generator transformer, unit transformer and excitation system. Depending on the nature of the fault, the X and Y protection can trip the generator circuit breaker, and in certain conditions, send inter-trip signals to Calvale substation, and trip the 6.6kV incomer circuit breakers.

[59] There is also a switch that allows the battery charger and battery to be connected directly to one another, without either the battery charger or battery being connected to the main switchboard. This gives the option for the battery charger to charge the battery directly, without supplying any of the Unit C4 loads. This is referred to as 'offline charging mode'.

[60] In normal conditions, the battery charger provides the current to any loads in the DC system and keeps the battery at a full state of charge. The battery may supply some current during dynamic changes in load, but the battery charger then adjusts its output to provide for this additional load, and the battery is then restored back to its full state of charge. This is explored in detail in Appendix A4.

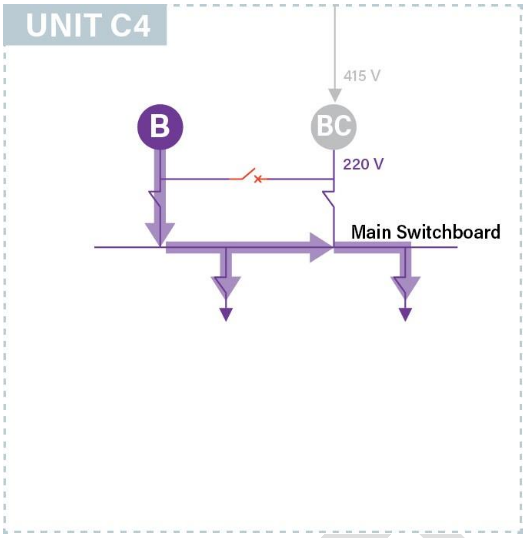

Figure 64 Battery supplying Unit C4

The Unit C4 battery can supply the DC system for several hours. This gives sufficient time for operators to respond and restore the battery charger output, or safely shut down the turbine generator.

5.5.5 Distribution Switchboard

The DC supply is routed from the main switchboard to the Unit C4 distribution switchboard, see Figure 65.

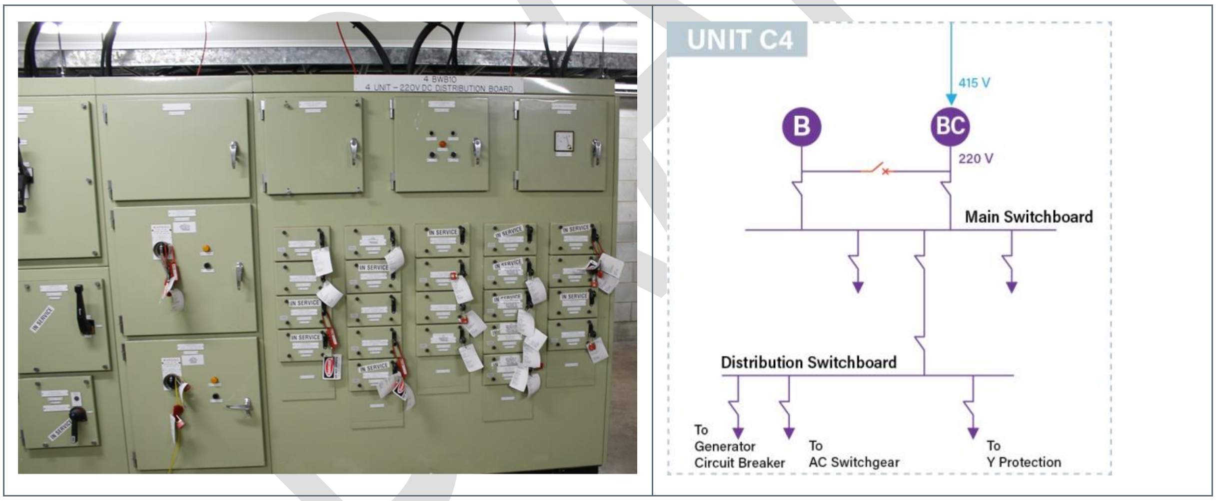

Figure 65 Unit C4 DC distribution switchboard

The Unit C4 distribution switchboard also distributes DC supply to a range of systems. It provides supply to part of the Unit C4 protection system, known as the 'Y protection system'. (Similar to the X protection system discussed above, the Y protection system also takes appropriate action when it detects an issue, such as safely shutting down the unit and disconnecting it from the grid.) The distribution switchboard also provides a second supply to the Unit C4 generator circuit breaker, and critically, it provides DC supply to various AC switches, allowing them to operate automatically or to be operated remotely from the control room.

5.6 Introduction to the Callide C DC System

5.6.1 Unit C3 and Station DC Systems

The Unit C3 and Station DC systems are both identical to Unit C4, see Figure 66.

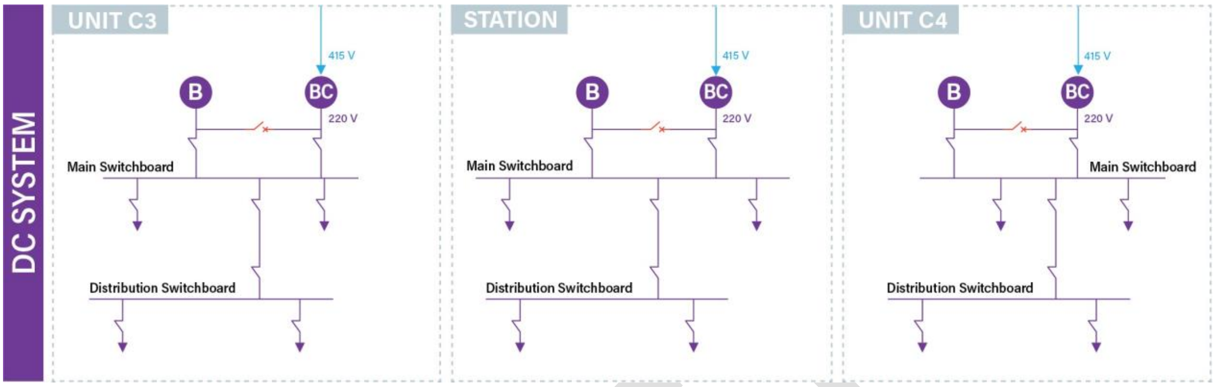

Figure 66 Callide C DC system

Unlike the Station AC system discussed above, which receives supply from Unit C3 and Unit C4, the Station DC system receives supply from its own battery charger and battery.

The DC system can be configured to interconnect each of the DC systems, via switches called ‘interconnectors’, see Figure 67.

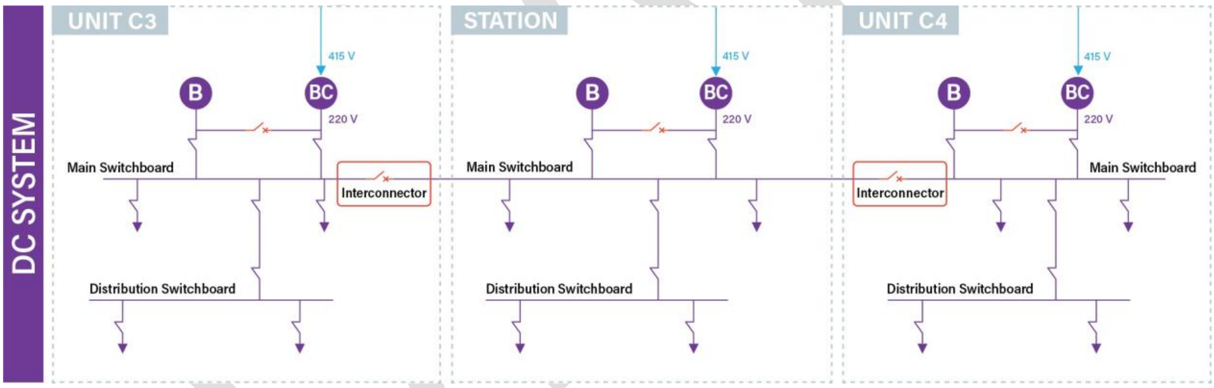

Figure 67 Interconnectors in Callide C DC system (indicated in red)

5.6.2 Automatic Changeover Switch

Each of the Station, Unit C3, and Unit C4 DC systems has a switch called the automatic changeover switch, which automatically responds and operates in the event of a loss of DC supply.

Figure 68 shows the automatic changeover switch on Unit C4.

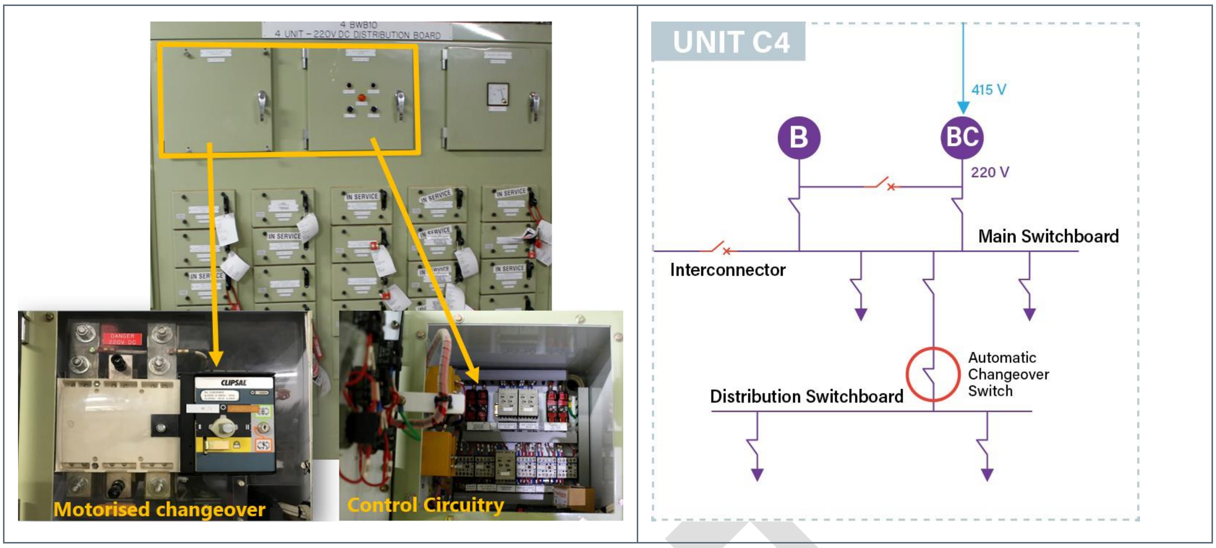

Figure 68 Unit C4 automatic changeover switch

As discussed above, the Unit C4 distribution switchboard supply is usually supplied from the Unit C4 main switchboard. This occurs via the automatic changeover switch, see Figure 69.

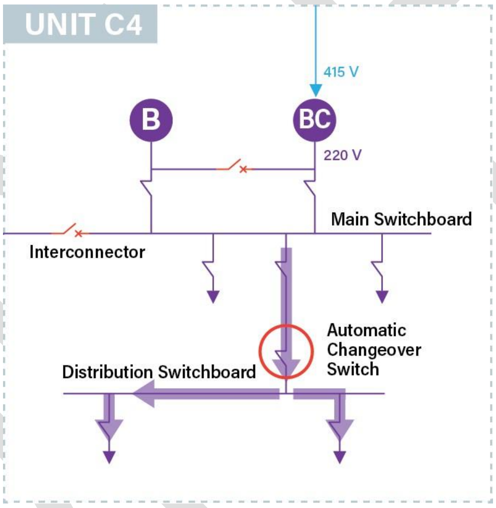

Figure 69 Unit C4 distribution switchboard supplied from the Unit C4 main switchboard

There is also a connection to the automatic changeover switch from the Station main switchboard, see Figure 70.

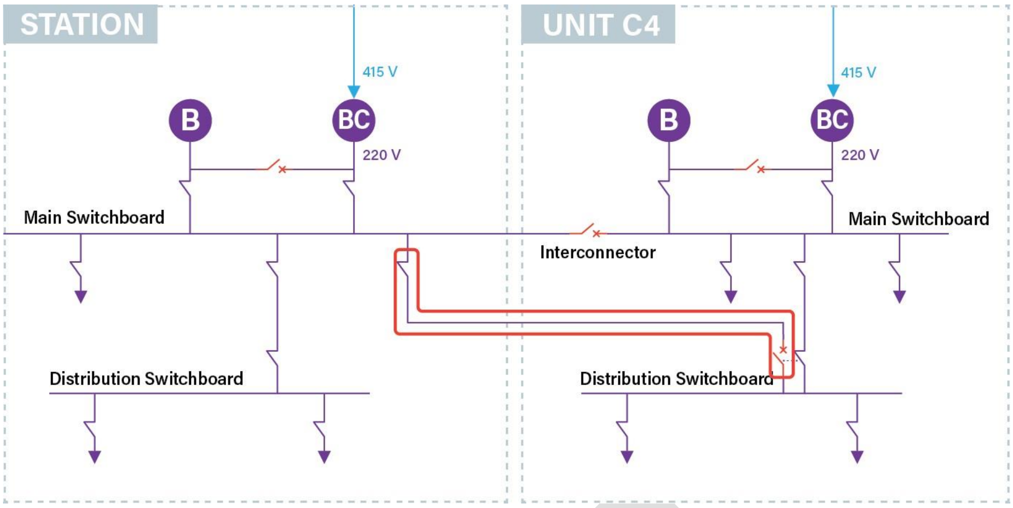

Figure 70 Automatic changeover switch also connects to Station main switchboard

If a loss of DC supply occurs in Unit C4, the automatic changeover switch can automatically operate and disconnect the unit distribution switchboard from the unit main switchboard. It then 'changes over' to supply the Unit C4 distribution switchboard from the Station main switchboard, see Figure 71.[61]

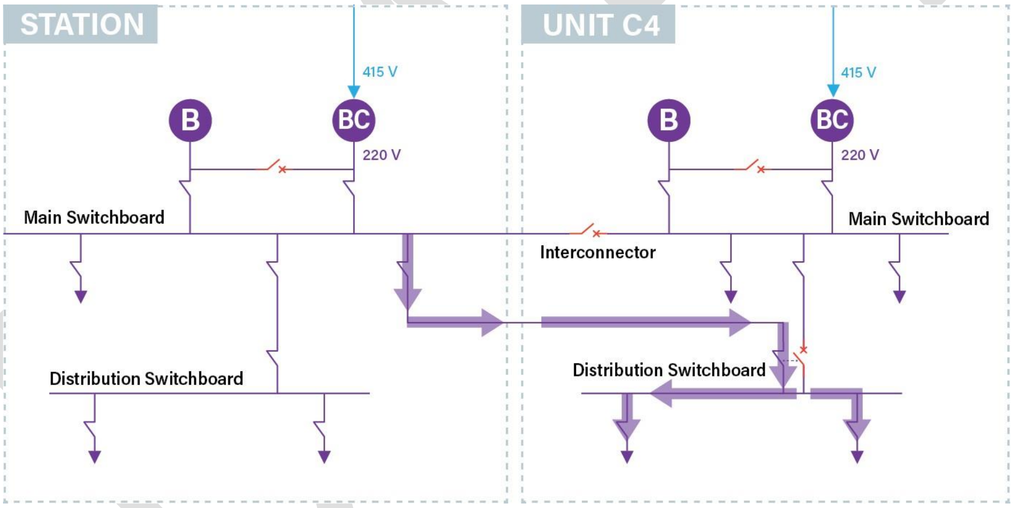

Figure 71 Unit C4 distribution switchboard supplied from the Station main switchboard

5.7 Relationship Between the Callide C AC and DC systems

While the Callide C AC and DC systems are separate, there is a relationship between these systems.

[61] The disconnection of the Unit C4 main switchboard before the connection of the Station main switchboard is referred to as 'break before make'. This changeover takes up to two seconds.

5.7.1 AC System to DC System Relationship

Within each DC system, the battery charger receives its AC supply from the corresponding AC system, as shown in Figure 72.

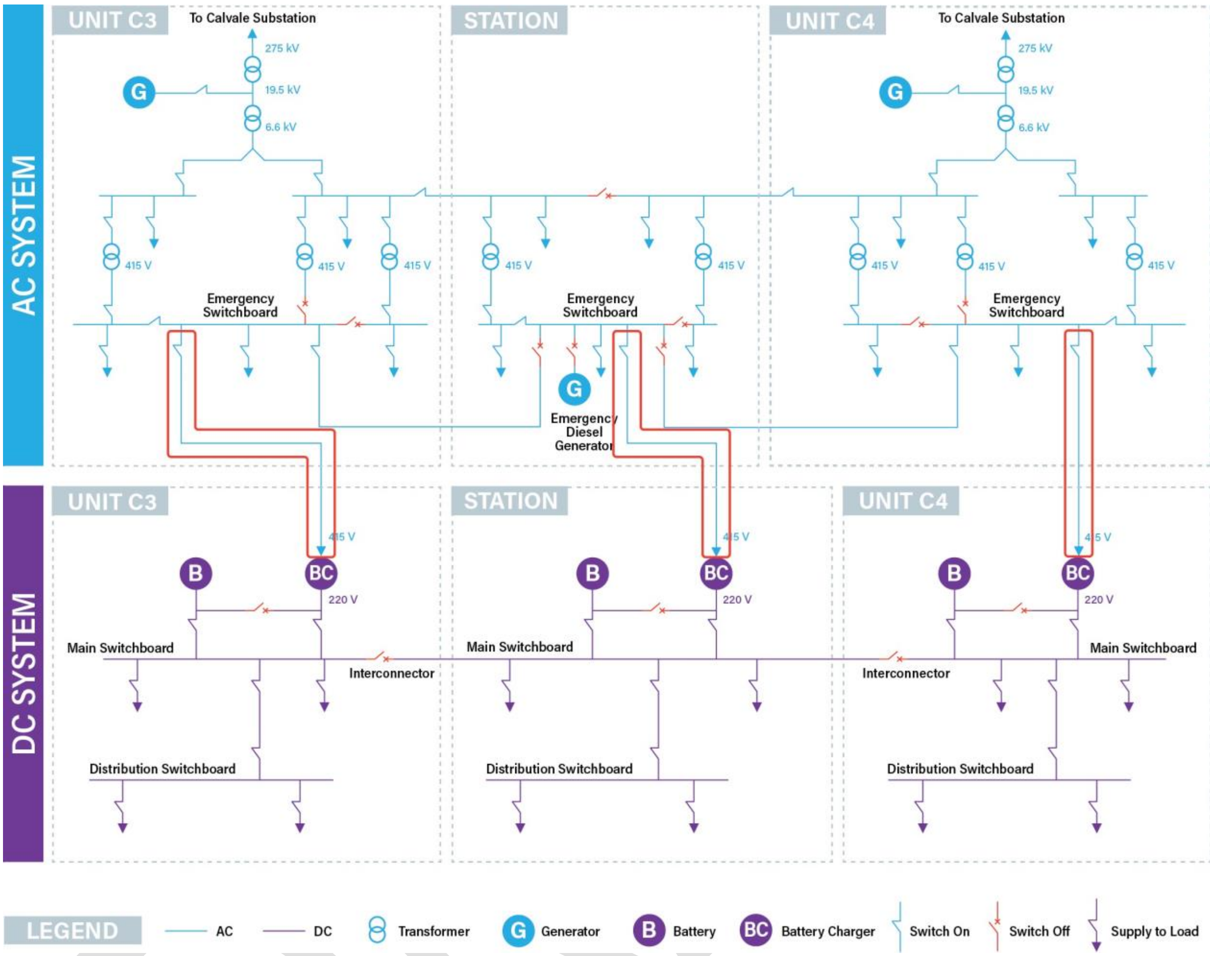

Figure 72 AC supply to each DC battery charger (indicated in red)

5.7.2 DC System to AC System Relationship

The AC system contains switches that require DC supply in order to operate automatically (or be operated remotely from the control room).[62] Each respective DC system provides this supply, and this will be discussed further in the next chapter.

5.8 Chapter Summary

This chapter has set out the relevant key components of the Callide AC and DC systems. The next chapter presents the switching sequence that was taking place on Unit C4 at the time of the incident.

[62] This includes the generator circuit breakers of Unit C3 and Unit C4, all the 6.6 kV AC circuit breakers, and a number of the 415 V AC circuit breakers.

6 THE ROLE OF THE SWITCHING SEQUENCE IN THE INCIDENT

6.1 Introduction

This chapter discusses the configuration of the Callide C electrical system during the switching sequence that was taking place on the day of the incident.

6.2 Background to the Switching Sequence

On the day of the incident, neither the Callide C AC system nor the Callide C DC system were in their typical configuration.

6.2.1 Callide C AC Configuration Prior to the Switching Sequence

In the typical configuration, both Unit C3 and Unit C4 provide AC supply to parts of the Station AC system, see Figure 73. The parts of the system supplied by Unit C4 are indicated by the arrows.

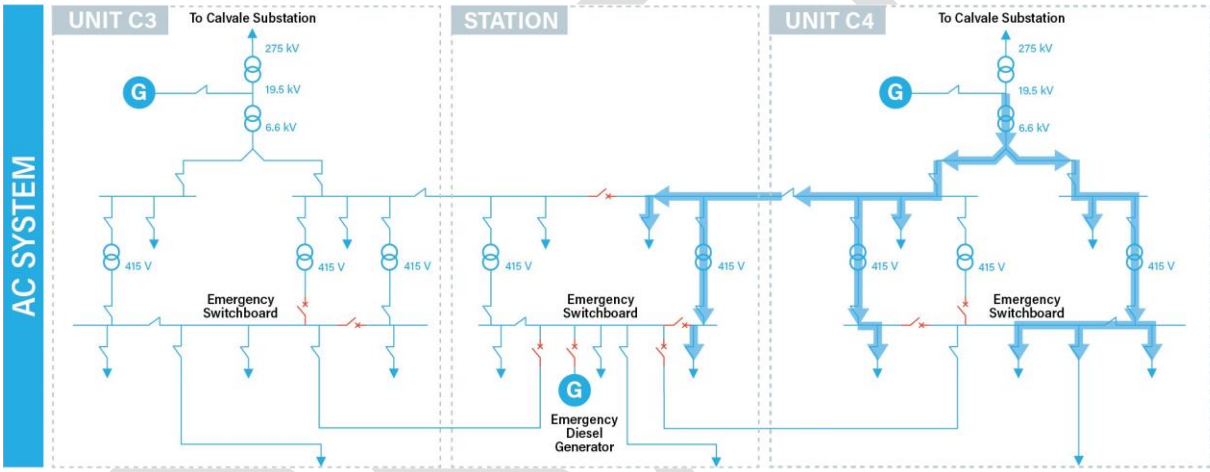

Figure 73 Typical Callide C AC system configuration

Figure 74 shows the configuration on the day of the incident, with the key differences indicated in red.

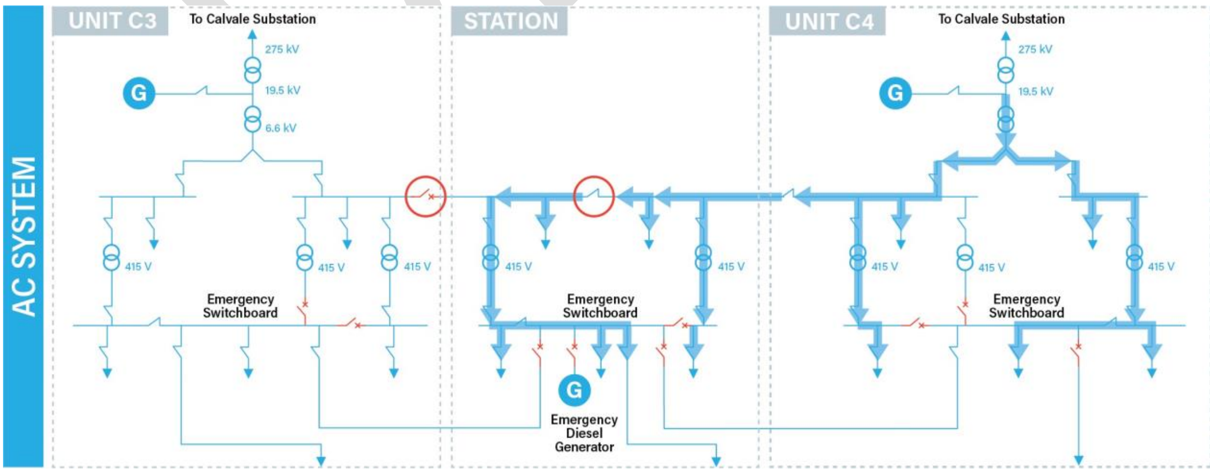

Figure 74 Callide C AC system configuration on the day of the incident

These key differences were:

- The 6.6 kV switch between Unit C3 and Station was open (off).
- The 6.6 kV switch on Station was closed (on).

This configuration was in place to facilitate maintenance of the 6.6 kV switch between Unit C3 and Station.

In this configuration, all Station AC supply was provided by Unit C4. This meant that if Unit C4 were to lose AC supply, Station AC would also be lost.

6.2.2 Callide C DC System Configuration Prior to the Switching Sequence

In the typical configuration, each DC system is supplied by a dedicated battery charger and battery. Figure 75 illustrates Unit C4 DC system being supplied by its own battery charger and battery.

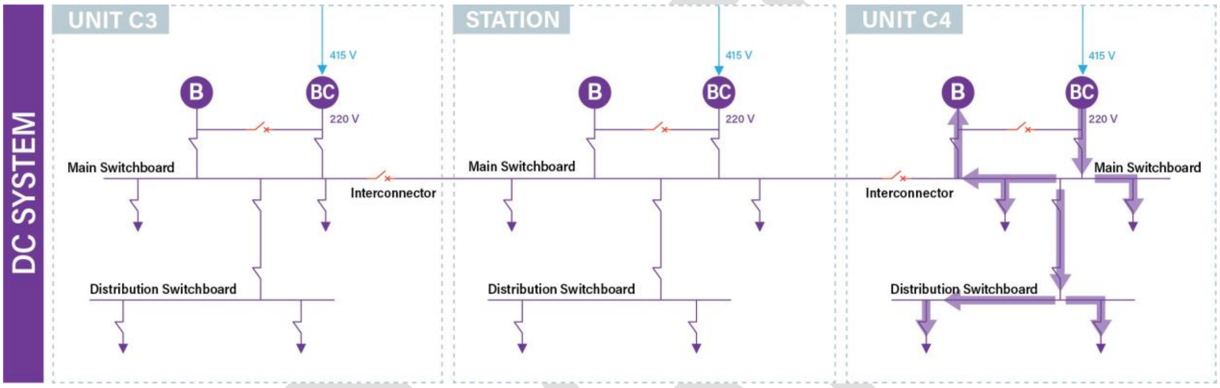

Figure 75 Typical Callide C DC system configuration

Figure 76 shows the configuration on the day before the incident, with the key differences indicated in red.

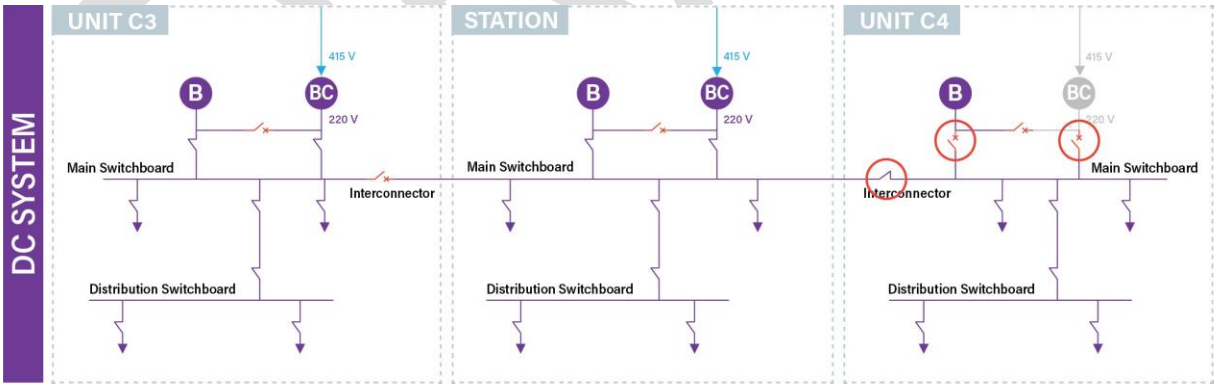

Figure 76 Callide C DC system configuration on the day before the incident

The key differences between the typical configuration and that on the day before the incident were:

- The Unit C4 battery charger and battery were disconnected from the Unit C4 main switchboard, and they were not providing supply.
- The interconnector between Station and Unit C4 was closed.

This meant that Station was providing all DC supply to Unit C4, see Figure 77.

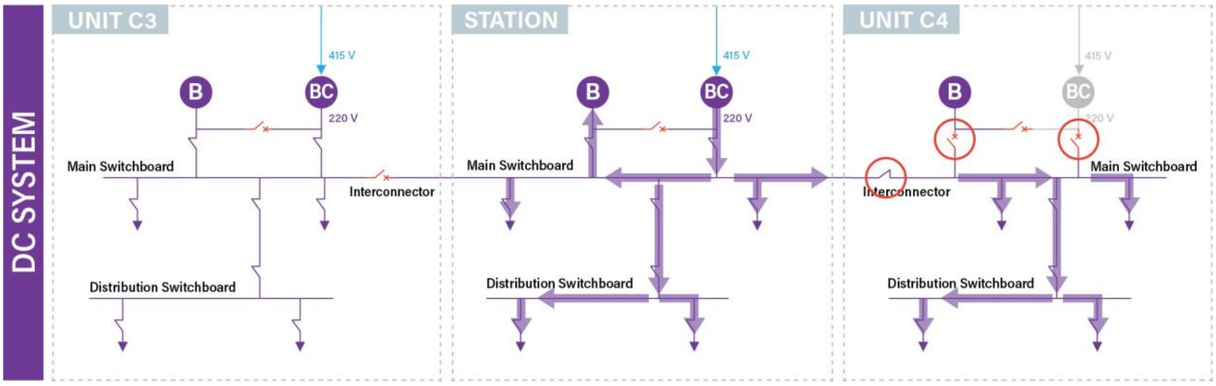

Figure 77 Callide C DC system configuration on the day before the incident

This configuration was in accordance with the design of the Callide C DC system, and was in place to facilitate the replacement of the Unit C4 battery charger, which had been underway since February 2021.

6.3 The Switching Sequence

6.3.1 Proposed Switching Sequence

A switching sequence to restore the Unit C4 DC system to its typical configuration commenced on 24 May 2021, the day before the incident.

This sequence involved connecting the replacement battery charger to Unit C4, disconnecting the Station DC supply from Unit C4, then connecting the existing Unit C4 battery to the unit. The battery charger and battery would then supply the Unit C4 DC system.

This was the first time that the replacement Unit C4 battery charger would be connected to the Unit C4 DC system.

6.3.2 Switching Sequence on 24 May 2021

This switching sequence began the day before the incident, on 24 May 2021, when the Unit C4 battery charger was connected directly to the battery to charge it overnight.[63] (The Unit C4 battery had been disconnected for three months, and it was no longer at full charge.) In this configuration, neither the battery charger nor battery were connected to the Unit C4 main switchboard, see Figure 78.

[63] This configuration is referred to as 'offline charging'.

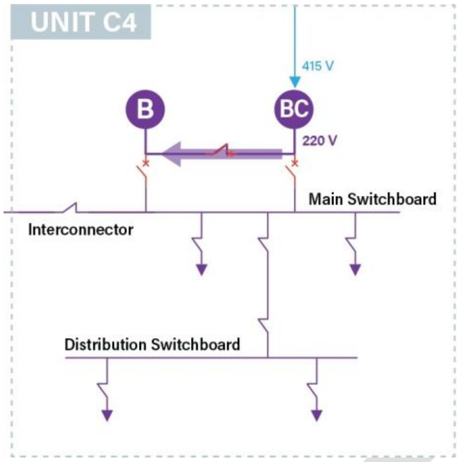

Figure 78 Offline charging on the day before and morning of the incident

6.3.3 Switching Sequence on 25 May 2021

Just before 1:30 pm on 25 May 2021, with the battery restored to a full state of charge, the switching sequence continued. The next step was to disconnect the Unit C4 battery charger from the battery, see Figure 79.

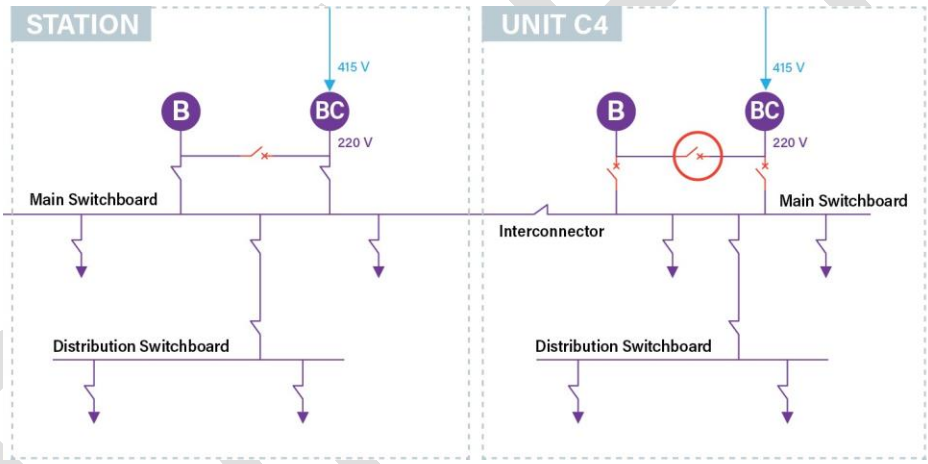

Figure 79 Disconnection of the Unit C4 battery from the Unit C4 battery charger

The next step was to connect the Unit C4 battery charger to the Unit C4 main switchboard, see Figure 80.[64]

[64] Connecting the battery charger to the main switchboard is referred to as bringing the battery charger 'online'.

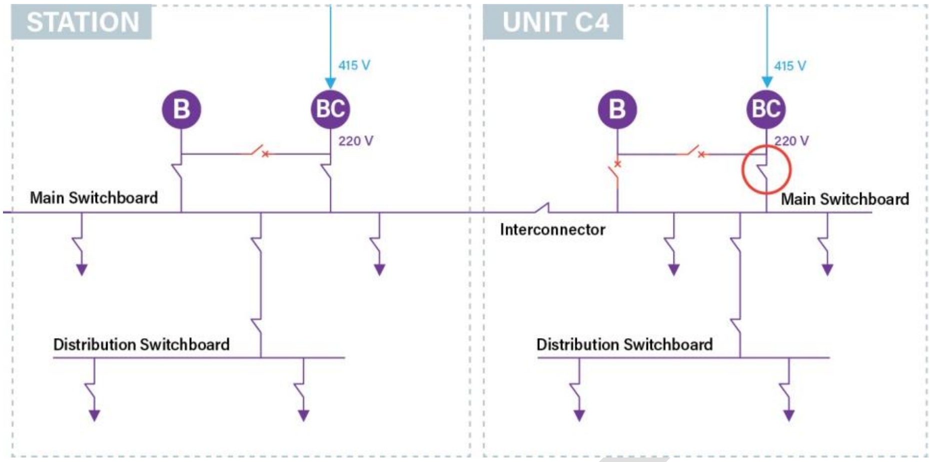

Figure 80 Connection of the Unit C4 battery charger to the Unit C4 DC system

At this point in the switching sequence, the Station and Unit C4 DC systems were still connected (via the interconnector), and then had three independent sources of supply available – the Station battery, the Station battery charger, and the Unit C4 battery charger.[65]

As will be discussed further in detail in Chapter 9, the Brady Heywood investigation determined that even though the Unit C4 battery charger was connected to and had the potential to supply the DC system, it was the Station battery charger that continued to provide all supply to the DC system at this time, see Figure 81.

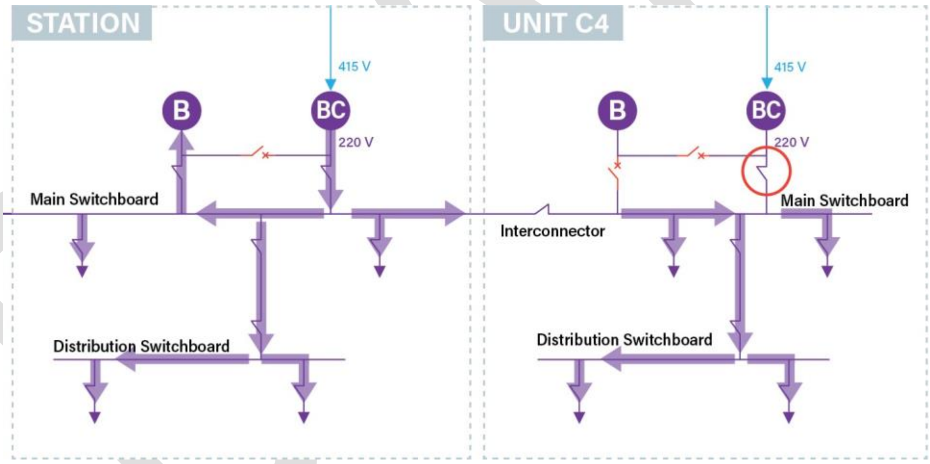

Figure 81 Station continues to provide all DC supply

The next step was to open the interconnector between the Station and Unit C4 DC systems.

When the interconnector was opened, this would result in the Station DC system no longer supplying Unit C4. The Unit C4 battery charger was therefore required to maintain the voltage in the DC system, as illustrated in Figure 82.

[65] Note that while there were three sources of supply available, this does not necessarily mean all three sources were supplying the loads in the (coupled) Station and Unit C4 DC system. A discussion on which sources were supplying the loads is contained in Appendix A6.

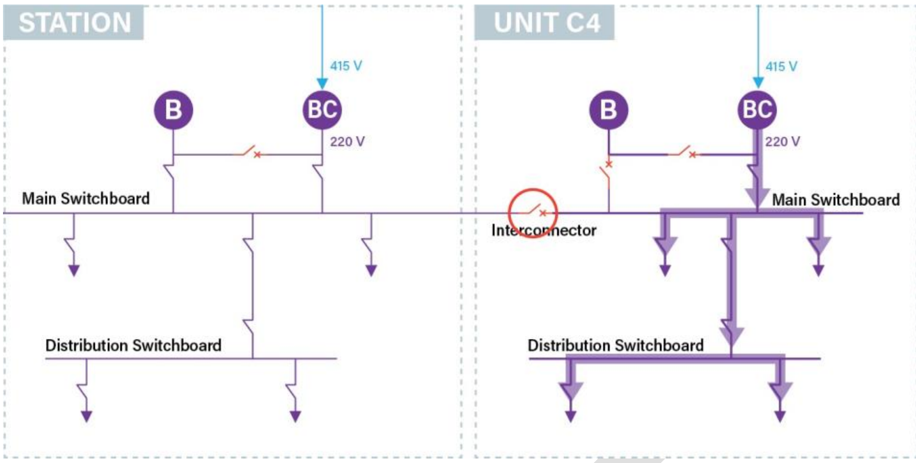

Figure 82 Opening of the interconnector between the Station and Unit C4 DC systems (required outcome)

This placed an implicit requirement on the battery charger to respond instantly and maintain the voltage in the Unit C4 DC system. (The term implicit is used because there is no evidence has been sighted that CS Energy explicitly considered this requirement, which will be discussed further in Chapter X [Batt Charger]). The Unit C4 battery charger was unable to respond instantly in this manner and initiated an almost instantaneous collapse of voltage in the Unit C4 DC system (which will be discussed in detail in the following chapters). At this point, the switching sequence was abandoned due to the unfolding situation at Unit C4.

Had the switching sequence proceeded as planned, the final step was to close the switch connecting the Unit C4 battery to the Unit C4 main switchboard, see Figure 83. This would have restored the Callide C DC system to its typical configuration.

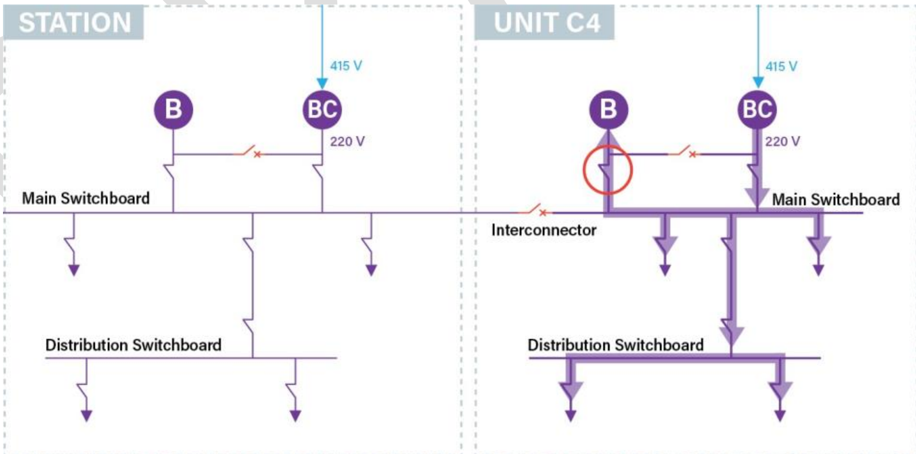

Figure 83 Planned connection of the Unit C4 battery to the Unit C4 DC system

6.3.4 A Note on the Switching Sequence

The switching sequence required the Unit C4 battery charger to provide DC supply to Unit C4 without the important redundancy provided by the battery. It was only *after* opening the interconnector that this redundancy would be restored by connecting the Unit C4 battery.

Had the Unit C4 battery been connected *before* opening the interconnector, it is very likely that it would have maintained the voltage in the DC system when the interconnector was opened.

While it may have appeared preferable to connect the Unit C4 battery prior to opening the interconnector, the design of the DC system did not permit the switching sequence to be carried out in this manner. This is because of the physical design of the plant, specifically the 'trapped key interlock system'.

The trapped key interlock system prevents more than one battery being connected to the same DC system.[66] With the interconnector closed, as it was at this point in the switching sequence, the Station and Unit C4 DC systems were combined into a single electrical system, with the Station battery connected.

The trapped key interlock system, therefore, physically prevented connection of the Unit C4 battery to this system. After the interconnector was opened, the Station and Unit C4 DC systems were then no longer joined into a single system, and the trapped key interlock system no longer prevented the Unit C4 battery from being connected.[67] At this point in the switching sequence the battery charger could be connected.

Although this switching sequence was prepared and executed in accordance with the limitations inherent in the DC system's design, there is no evidence to suggest that, prior to planning and executing the switching sequence on the day of the incident, CS Energy specified, tested or considered the ability of the battery charger to operate as the sole source of supply (and maintain the voltage in the DC system under the dynamic conditions of switching).[68]

6.4 Chapter Summary

This chapter presented the switching sequence that was taking place at the time of the incident, specifically how it required the Unit C4 battery charger to maintain the voltage in the Unit C4 DC system when it became the sole source of supply to that system.

The next chapter examines the role played by the Unit C4 DC and AC systems during the execution of this switching sequence.

[66] A trapped key interlock system prevents certain switches from being operated unless other switches are in a known and proven state. It does this by requiring a key to operate certain switches, which are then 'trapped' in the switch. Other switches that require that key cannot then be operated without first reversing the operation on the first switch and releasing the trapped key.

[67] Other switching sequences may have been possible, such as disconnecting the Station Battery and connecting the Unit C4 battery prior to opening the interconnector, but these hypothetical scenarios are not discussed in this technical report.

[68] The Brady Heywood investigation determined that under the specific conditions on the day, the battery charger was not capable of responding instantly and maintaining the voltage in the Unit C4 DC system.

7 THE ROLE OF THE ELECTRICAL SYSTEM IN THE INCIDENT

7.1 Introduction

This chapter discusses how the Callide C electrical system responded during the switching sequence, specifically focusing on how the loss of supply to parts of the Callide C DC and AC systems led to the incident.

7.2 Loss of Supply in the Callide C Electrical System

The opening of the interconnector led to the following sequence of events:

- The voltage in the Unit C4 DC system collapsed from ~243 V to ~120 V.
- This collapse in DC voltage led to the loss of AC supply to Station and Unit C4 (to ~0 V).
- The loss of AC supply led to the complete loss of DC supply to Unit C4 (to ~0 V).

This sequence is discussed further in the sections below.

7.2.1 The Collapse of DC Voltage in Unit C4

The opening of the interconnector between the Unit C4 and Station DC systems initiated the incident. Immediately prior to this point in the switching sequence, there were three sources of supply available to maintain the voltage in the interconnected Station and Unit C4 DC systems – the Station battery, the Station battery charger, and the Unit C4 battery charger. Of these three available sources, it was only the Station battery charger that was supplying the Unit C4 DC system at this time.[69]

When the interconnector was opened, the Unit C4 battery charger became the sole source of DC supply to Unit C4. This requirement meant the Unit C4 battery charger needed to respond instantly and supply the Unit C4 DC system. The battery charger did not respond in this manner.[70] When the interconnector was opened, the voltage in Unit C4 DC system collapsed to ~120 V, see Figure 84.

[69] There is no evidence to indicate that the switching sequence was planned or carried out with the intention (or knowledge) that the Station battery charger would continue to provide all supply to the DC system after the Unit C4 battery charger was connected. Conversely, there is no evidence that indicates that there was an intention for the Unit C4 battery charger to provide any (or all) supply to the DC system after it was connected either.

[70] This ability was not something that the battery charger had been specified or tested as being capable of doing.

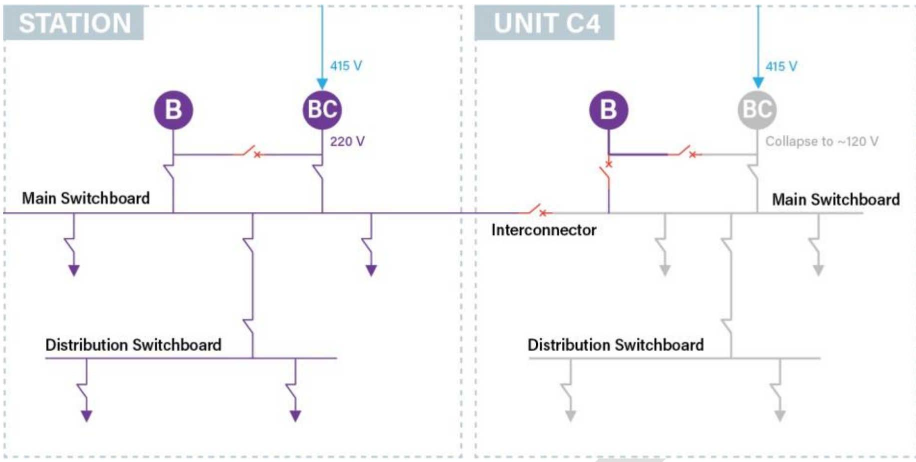

Figure 84 Collapse of DC supply to Unit C4 DC system (shown in grey)

A detailed discussion of why the battery charger behaved in this manner is provided in Chapter 9. The remainder of this chapter focuses on the consequences of the loss of DC and AC.

7.2.2 The Loss of AC Supply to Unit C4 and Station

The collapse in voltage in the Unit C4 DC system directly led to the loss of AC supply to the Unit C4 and Station AC systems. The precise manner in which this loss occurred is discussed in detail in Section 8.1, but in simple terms, the DC voltage collapse caused the two 6.6 kV AC incomer circuit breakers in the Unit C4 AC system to trip (open automatically), as indicated in red in Figure 85.

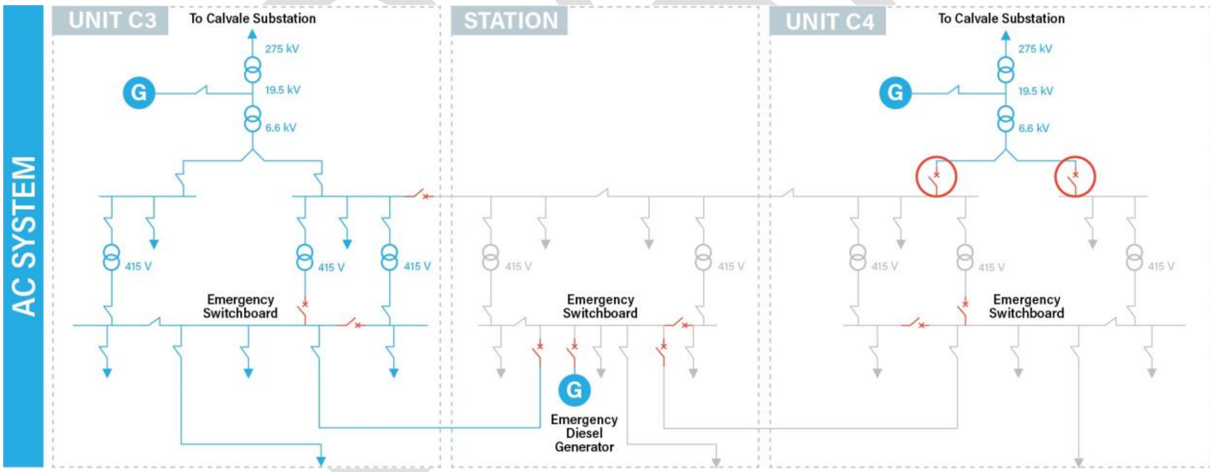

Figure 85 Unit C4 AC 6.6 kV incomer circuit breakers trip (open)

The opening of the AC incomer circuit breakers resulted in a complete loss of AC supply to the Station and Unit C4 AC systems, as indicated by grey in the figure above.

7.2.3 The Loss of DC Supply to Unit C4

While it was the opening of the interconnector that led to the voltage collapse (to ~120 V) in the Unit C4 DC system, it was the subsequent loss of AC supply to Unit C4 that led to the complete loss of DC supply.

Because the Unit C4 battery charger was supplied with AC from the Unit C4 emergency switchboard, the loss of AC supply to that switchboard resulted in a loss of AC supply to the Unit C4 battery charger, see Figure 86.

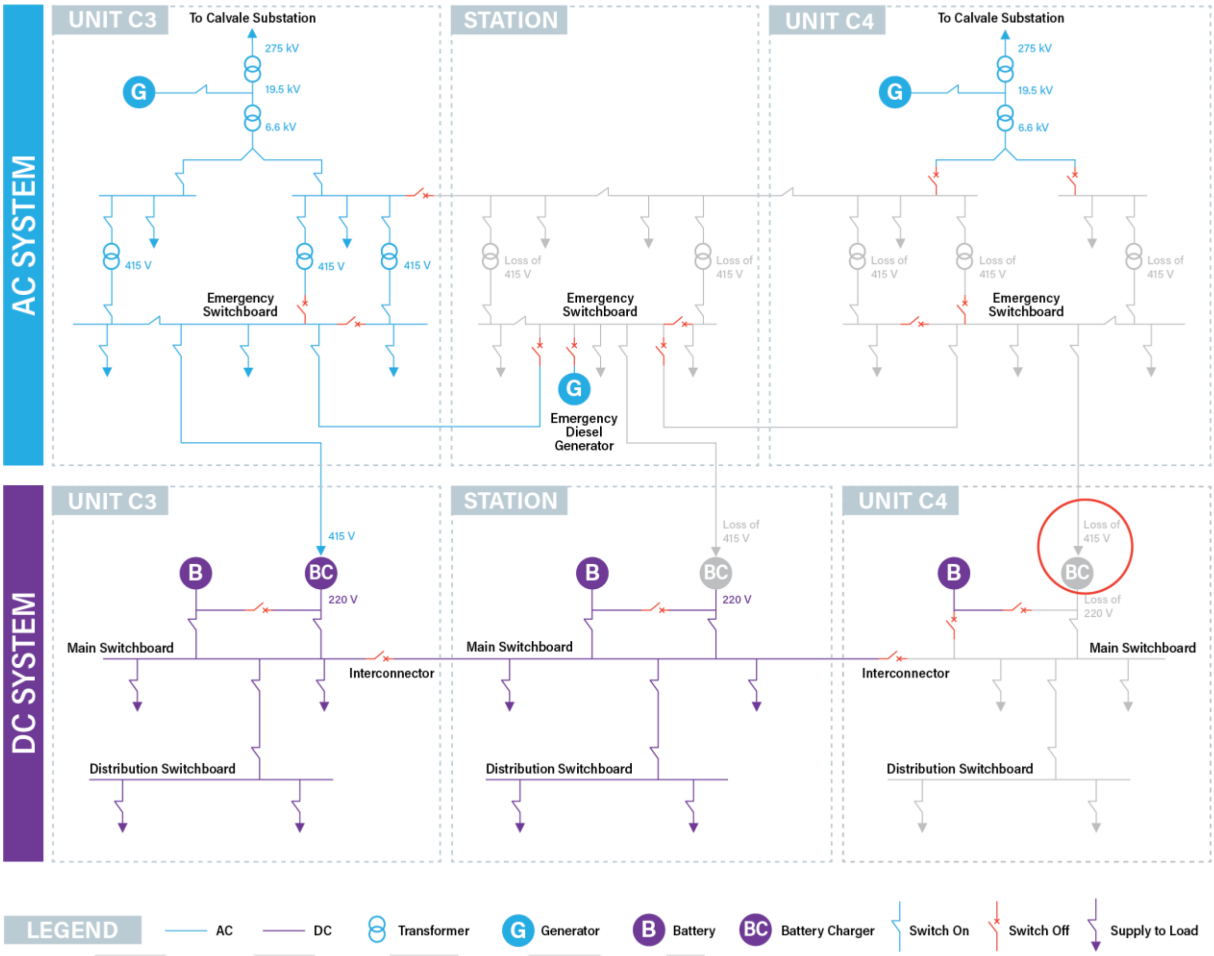

Figure 86 Loss of AC supply to Station and Unit C4 battery chargers

Had the Unit C4 battery charger's AC supply been maintained, it is likely that it would have restored the DC system voltage to its usual level within 2 seconds. However, the loss of AC supply resulted in the Unit C4 battery charger shutting down before it could restore the DC system voltage.[71]

7.2.4 Summary

The opening of the interconnector led to a voltage collapse in the Unit C4 DC system. This voltage collapse led to the loss of AC supply to Station and Unit C4. The loss of AC supply led to the inability of the battery charger to recover the voltage in the Unit C4 DC system, leading to a complete loss of supply in the Unit C4 DC system.

[71] The figure also illustrates that the loss of Station AC supply resulted in the loss of AC supply to the Station battery charger. DC supply to Station was not lost, however, because the Station battery was still connected and able to maintain supply.

7.3 Consequences of the Loss of Supply in the Callide C Electrical System

The following sections discuss the consequences of the DC collapse, AC loss and DC loss.

7.3.1 Consequences of the Collapse of DC Voltage in Unit C4

While multiple items of equipment became unavailable at the time of the voltage collapse in Unit C4 DC system, the key consequence of the collapse was the loss of AC supply to the Unit C4 and Station AC systems.[72]

7.3.2 Consequences of the Loss of AC Supply to Unit C4 and Station

The loss of 6.6 kV and 415 kV AC supply led to the loss of multiple pieces of equipment.[73]

Significant to the incident was:[74]

- The loss of the AC steam valve hydraulic pumps, resulting in a loss of hydraulic oil pressure, causing the turbine's steam valves to shut. (The loss of steam was a necessary step for motoring to occur).
- The loss of the AC lubrication oil pumps, resulting in a loss of lubrication oil pressure to supply oil to the bearings.
- The loss of the AC seal oil pump, resulting in a loss of seal oil pressure to the seals that prevent hydrogen from escaping from the generator.
- The loss of all cooling systems (auxiliary cooling water, treated cooling water, stator coolant, transformer cooling fans and oil pumps, etc.), resulting in a build-up of heat.
- The loss of 415 V AC supply to the Unit C4 battery charger, resulting in the inability of the battery charger to recover the voltage in the DC system, leading to the loss of DC supply to Unit C4.

7.3.3 Consequences of the Loss of DC Supply to Unit C4

The loss of DC supply (~0 V) resulted in the loss of both the Unit C4 main switchboard and the Unit C4 distribution switchboard, see Figure 87.

[72] This is discussed in Section 8.1.

[73] In the 6.6 kV AC system, this includes the loss of the boiler (which tripped, placing the boiler in a safe state), the loss of the main cooling water pump (which resulted in the loss of cooling for the condenser), the loss of water flow through the units (condensate/feedwater, etc.), and the loss of two of the three control air compressors (which led to the eventual trip of Unit C3. It also led to the loss of the unit extract pumps).

[74] These pieces of equipment were supplied by 415 V AC.

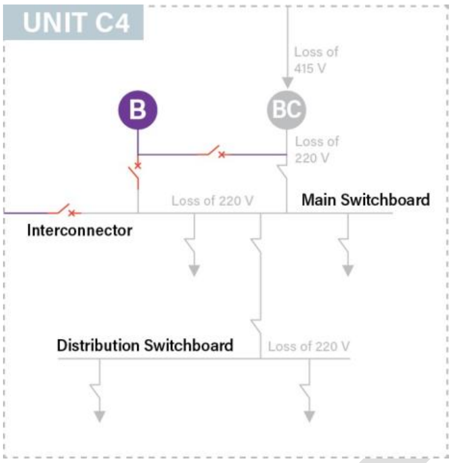

Figure 87 Supply lost to Unit C4 main switchboard and distribution switchboard

The loss of DC supply to the Unit C4 main switchboard led to several key consequences:

- The loss of the DC emergency lubrication oil pump. This, combined with the loss of the AC lubrication oil pumps, meant that no lubrication oil was provided to the bearings. Without lubrication oil, the bearings began grinding metal-on-metal.
- The loss of the DC emergency seal oil pump. This, combined with the loss of the AC seal oil pump, meant that no seal oil was provided to the hydrogen seals in the generator. Without seal oil, the hydrogen began escaping to the surrounding air.
- The loss of Unit C4 X protection. This resulted in the partial loss of ability to detect issues in Unit C4 and shut it down safely.
- The loss of the first of two DC supplies to Unit C4 generator circuit breaker.
- The loss of supply to the Unit C4 distribution switchboard, which was being supplied by Unit C4 main switchboard.

The loss of DC supply to the Unit C4 DC distribution switchboard led to the following consequences:

- The loss of Unit C4 Y protection. This resulted in the complete loss of ability to detect issues in Unit C4 and shut it down safely.
- The loss of the second of two DC supplies to the Unit C4 generator circuit breaker. This resulted in the inability to open the Unit C4 generator circuit breaker and disconnect from the grid.[75]
- The loss of the ability to trip the Calvale substation 275 kV circuit breakers.[76] Calvale could not automatically trip or be tripped from Unit C4. Unit C4 remained connected to the grid.
- The failure to restore AC supply to the Unit C4 emergency switchboard by the emergency diesel generator.

[75] It is unclear if the generator circuit breaker has the ability to be operated manually without DC supply.

[76] The X protection also has the ability to initiate a trip of at Calvale substation, but the X protection system was lost due to the loss of the main switchboard.

7.4 A Note on Why Station DC Supply Was Not Lost

While the loss of Station AC supply led to the Station battery charger shutting down, Station DC was not lost during the incident because the Station battery remained connected to the system, see Figure 88.

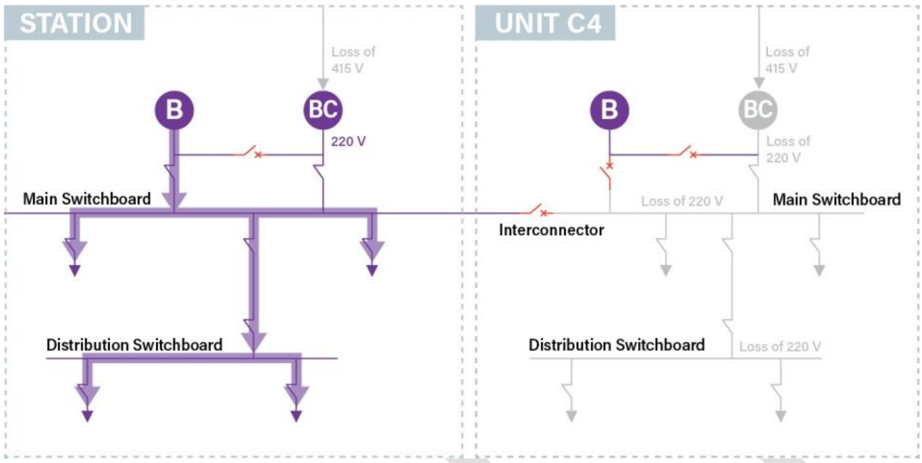

Figure 88 Station DC supply maintained by the Station battery while Station AC was lost

Maintaining supply to the Station DC system had important ramifications for the operation of the emergency diesel generator, as will be discussed in the next section.

7.5 The Role of the Emergency Diesel Generator in the Incident

7.5.1 Introduction

Callide C has an emergency diesel generator that forms part of the Station AC system. In the event of a loss of AC supply, the emergency diesel generator is supposed to operate and restore 415 V AC to the affected system's emergency switchboard.

On the day of the incident, however, while the AC supply was restored to Station, it was not restored to Unit C4.

7.5.2 The Restoration of Station AC Supply

As discussed above, when the AC supply was lost to Unit C4 this also led to a loss of AC supply to Station, see Figure 89.

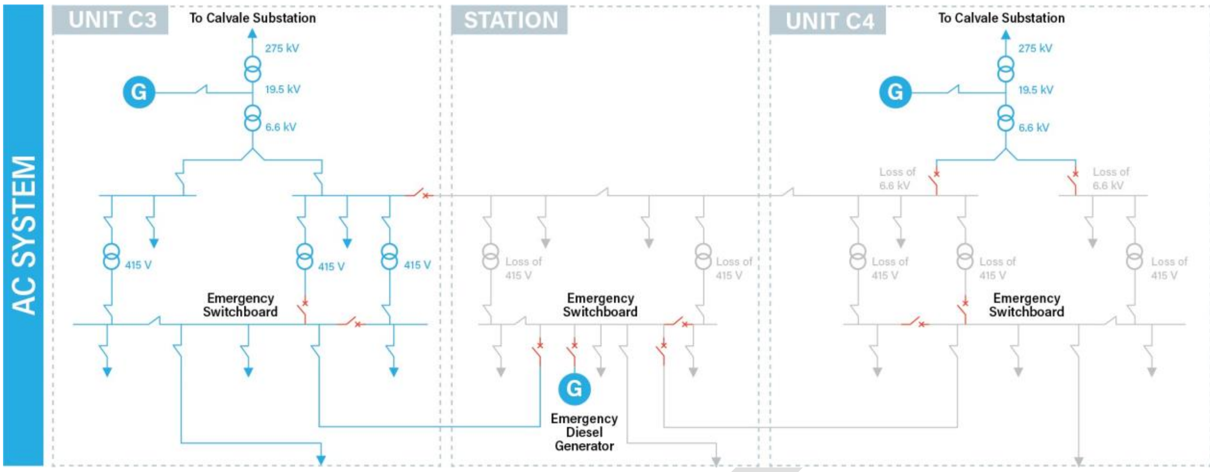

Figure 89 Loss of AC supply to Unit C4 and Station

This resulted in the emergency diesel generator operating and generating AC supply. The emergency diesel generator, however, still needed to connect to the Station emergency switchboard. For this to occur, it was necessary to configure switches in the Station AC system so that this AC supply could be safely received by the emergency switchboard.[77] This configuration (of the Station AC system) is carried out by switchgear that is powered by the Station DC system, see Figure 90.[78]

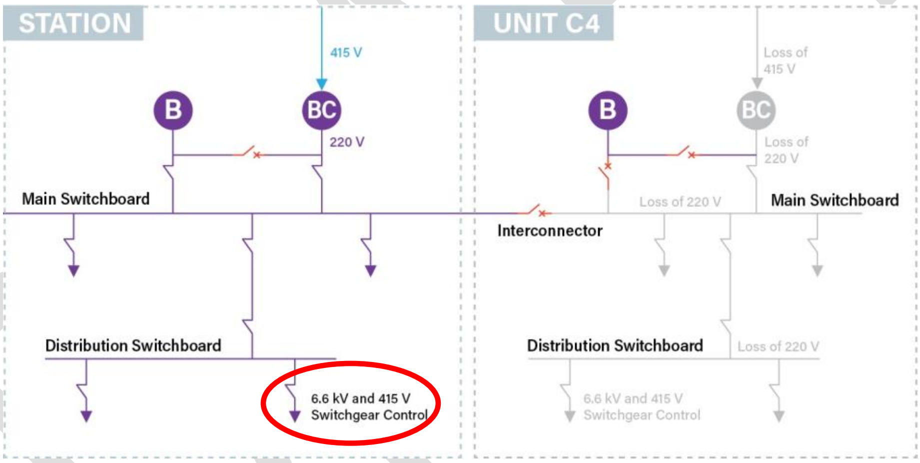

Figure 90 Availability of DC supply to Station AC switchgear

As discussed above, while AC supply to Station was lost in the incident, DC was not. DC supply was therefore available to operate the Station 415 V switchgear.[79] Within 25 seconds, the Station 415 V switchgear operated and reconfigured the Station emergency switchboard to receive supply from the

[77] In order to configure the Station emergency switchboard to receive supply from the emergency diesel generator, it is necessary to ensure all other switches from alternate sources of supply (to the emergency switchboard) are open. This is to avoid, for example, the overloading of the diesel generator, or the Station emergency switchboard back-feeding onto the Station 6.6 kV switchboard (through the 6.6 kV to 415 V transformers).

[78] There are separate supplies to the switchgear on each of the 6.6 kV AC switchboards and the 415 V AC switchgear. For simplicity these have been shown as a single switch and load in this diagram.

[79] While the loss of Station AC led to a loss of the Station battery charger, the Station battery remained, providing supply to the DC system.

emergency diesel generator. AC supply was therefore successfully restored to the Station emergency switchboard, see Figure 91.

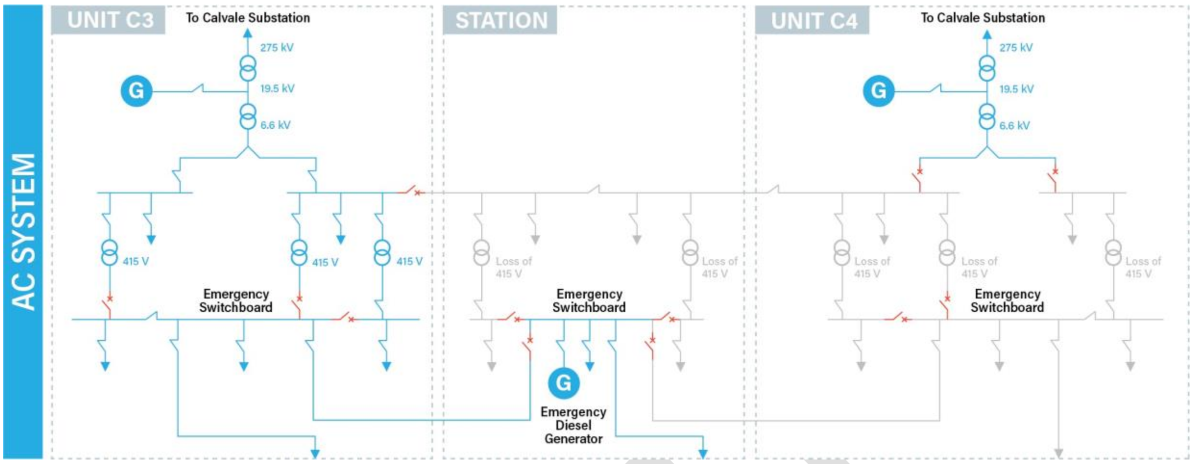

Figure 91 Emergency diesel generator restores AC supply to Station 415 V emergency switchboard

The restoration of AC supply to the Station emergency switchboard restored supply to the Station battery charger. The Station battery charger then supplied Station DC loads and restored charge to the Station battery. This meant that in the first ~50 seconds of the incident, AC was partially restored to Station and the Station battery charger's functionality was restored.

7.5.3 The Failure to Restore Unit C4 AC Supply

Without DC supply, however, the Unit C4 switchgear couldn't operate, see Figure 92.[80]

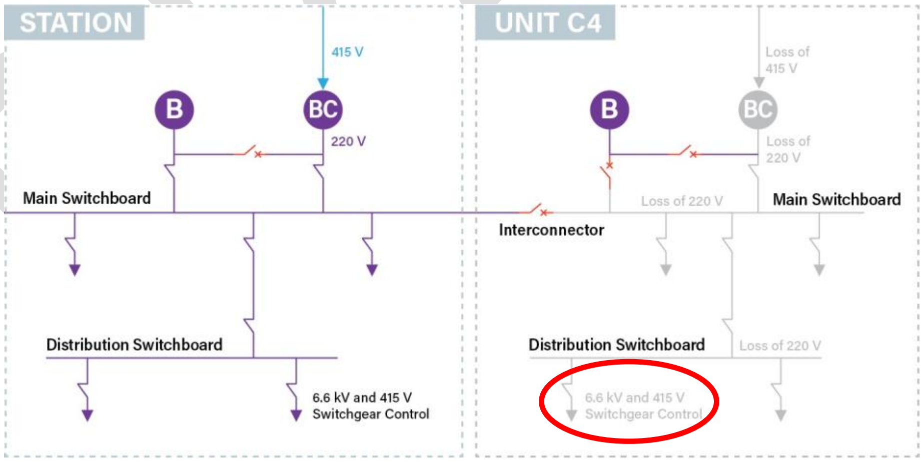

Figure 92 Loss of DC supply to Unit C4 AC switchgear

[80] As with Station, there are separate supplies to the switchgear on each of the 6.6 kV AC switchboards and the 415 V AC switchgear. For simplicity these have been shown as a single switch and load in this diagram.

Figure 93 illustrates some of the AC switches that could not be configured as a result, indicated in red.[81]

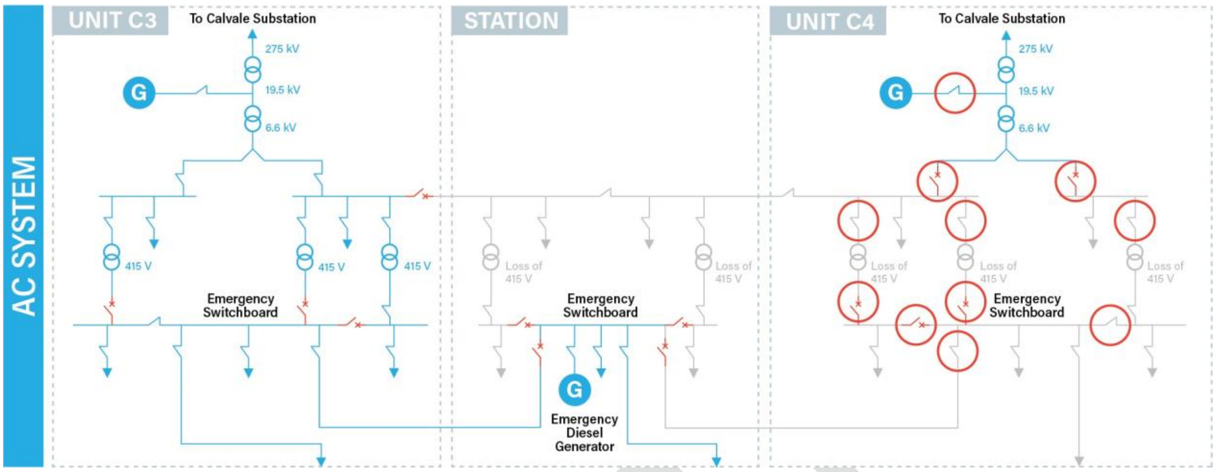

Figure 93 Switches in the Unit C4 AC system could not be configured due to loss of DC supply

Without an ability to reconfigure these Unit C4 AC switches, AC supply from the emergency diesel generator (via the Station emergency switchboard) could not be restored to the to the Unit C4 emergency switchboard.

7.6 The Role of the Automatic Changeover Switch in the Incident

7.6.1 Introduction

If DC supply in Unit C4 is lost, the automatic changeover switch can automatically operate and 'change over' to supply the Unit C4 distribution switchboard from the Station main switchboard, Figure 94.

[81] While the switchgear couldn't operate automatically or be operated from the control room, it may have been technically possible to operate some switchgear manually. This was not necessarily a feasible option at the time, as it would have required personnel to go the switchgear's location.

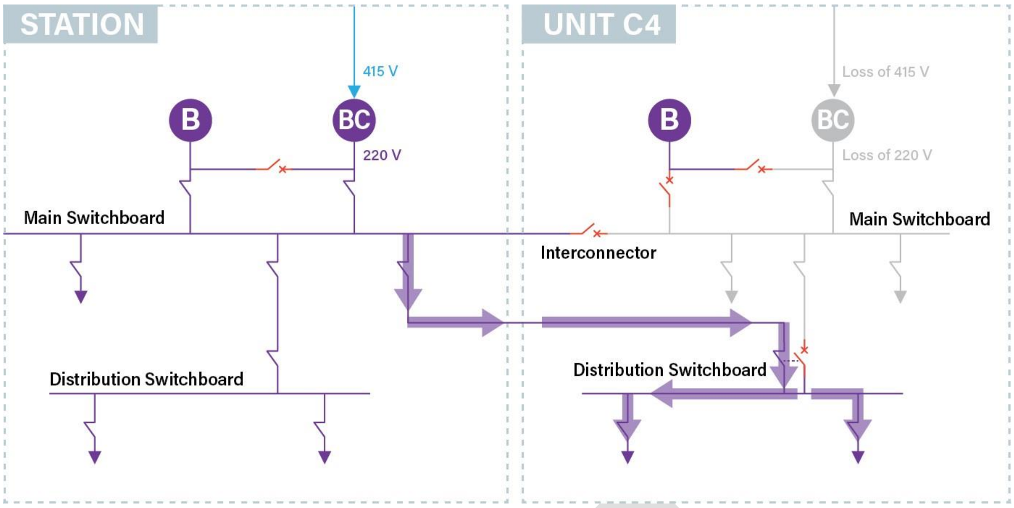

Figure 94 Unit C4 distribution switchboard supplied from the Station main switchboard

7.6.2 Status of the Automatic Changeover Switch on the Day of the Incident

As discussed in Section 4.3, the automatic changeover switch was damaged and inoperable in automatic mode on the day of the incident.

7.6.3 Potential Consequences of Lack of Functionality of Automatic Changeover Switch

Had the automatic changeover switch been operational in automatic mode, and had it successfully changed over to supply Unit C4 distribution switchboard from Station, a different outcome to the incident is conceivably possible.

This outcome is generally speculative and highly dependent on the exact set of assumptions. It is explored in more detail in Section XX (electrical appendix).

The following sequence of events is likely if the Unit C4 automatic changeover switch had been operational (and successfully operated) on the day of the incident.[82]

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[82] Even if the Unit C4 automatic changeover switch had been repaired and operational in automatic mode on the day of the incident, it is not clear if it would have successfully operated and restored DC supply to the Unit C4 distribution switchboard. This is because it became known throughout the Brady Heywood investigation that the automatic changeover switches in Callide C were prone to reliability issues inherent in the design of the control circuitry. These reliability issues could result in the motor of the automatic changeover switch being supplied with a voltage higher than its rated voltage, causing the fuses that provide power to the automatic changeover switch's control circuitry (and motor) to blow mid-way through a change-over operation. This leaves the associated distribution switchboard without supply from either of the two main switchboards that the automatic changeover switch connects to.

The Unit C3 automatic changeover switch was tested by CS Energy after the incident, and reported to have failed mid-way through the first operation (leaving the Unit C3 distribution switchboard without supply).

The Station automatic changeover switch was tested as part of the Brady Heywood investigation, and successfully changed over once, but failed mid-way through the second operation (leaving the Station distribution switchboard without supply).

The Unit C4 automatic changeover switch was tested as part of the Brady Heywood investigation, but failed to change over due to the control circuitry being damaged (likely a result of a separate incident in January 2021). In order to facilitate testing as part of the Brady Heywood investigation, CS Energy repaired the Unit C4 automatic changeover switch (using parts from the Station automatic changeover switch control circuitry), but in doing so exposed the Unit C4 automatic changeover switch to the

- The collapse in DC supply would likely still result in a loss of AC supply to Unit C4 and Station. This would occur in the same manner as it did on the day of the incident (by the arc flap protection activating).
- The loss of AC supply would likely still result in a loss of DC supply to Unit C4.
- Unit C4 would have likely still remained connected to the grid, and would have begun to transition to motoring with a loss of lubrication oil and seal oil.[83]
- If the Unit C4 automatic changeover switch had then operated successfully, DC supply likely would have been restored to the Unit C4 distribution switchboard within ~2 seconds. (DC supply would not have been restored to the main switchboard, which means that the emergency lubrication oil and seal oil pumps, which are supplied from the main switchboard, would still not have operated.)
- The restoration of Unit C4 DC distribution switchboard would have likely restored the Y protection system. After the Y protection powered up, it would have had several mechanisms to detect that Unit C4 was in fault, and likely would have responded by attempting to open the generator circuit breaker and disconnect Unit C4 from the grid.
- The DC supply from the Unit C4 DC distribution switchboard to the generator circuit breaker is likely to have had blown fuses.[84] It is therefore unlikely that the generator circuit breaker would have operated, and Unit C4 would have likely remained connected to the grid.
- The Y protection system would have likely detected that the generator circuit breaker had not operated, and would have likely sent an inter-trip signal to Calvale substation. The protection system at Calvale substation should have then likely operated and disconnected Unit C4 from the grid at Calvale.[85]
- It is not likely that the lubrication oil would have been restored (by the emergency diesel generator restoring supply to the AC lubrication oil pumps via the emergency switchboard).[86]

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same conditions conducive to the over-voltage failure inherent in the design of the control circuitry. Subsequent testing as part of the Brady Heywood investigation showed that the Unit C4 automatic changeover switch successfully operated multiple times. It was discovered that that the control circuitry had still failed, but in such a manner that the voltage supplied to the motor of the Unit C4 automatic changeover switch was lower than its rated voltage, rather than higher. While this caused the Unit C4 automatic changeover switch to operate much slower than normal, it did not result in blown fuses and therefore did not cause the Unit C4 automatic changeover switch to fail mid-way through an operation. It could not be determined if the failure that led to the under-voltage of the motor (and reliable operation of the Unit C4 automatic changeover switch) occurred prior to the 25 May 2021 incident, or during the repair that occurred as part of the Brady Heywood investigation.

[83] The rotor of the turbine generator would have needed to slow in speed slightly in order for the unit to transition from generating to asynchronous motoring.

[84] CS Energy became aware in March 2024 that the fuses supplying the Unit C4 generator circuit breaker from the Unit C4 distribution switchboard were blown. It is likely that these fuses were blown on the day of the incident (or during the incident). Note, these fuses are not to be confused with the fuses on the automatic changeover switch, discussed in Section X.

[85] Confirming the successful operation of the inter-trip signal at Calvale substation under this hypothetical scenario was not considered part of the investigation.

[86] AC supply to the AC lubrication oil pumps is likely to have been momentarily restored by the following mechanism:

- From this point, Unit C4 would slowly spin down with no lubrication oil (leading to the shaft and bearings grinding metal-on-metal) and with no seal oil (leading to the hydrogen escaping from the generator). This could cause significant damage to the shaft and rotor, but the turbine missile event would likely not have occurred. The spin-down time depends on many factors, (such as the amount of friction produced from the shaft and bearings), but is possibly in the order of ~10 minutes).
- The generator rotor may sustain significant damage, although the stator damage is likely to be much less than what actually eventuated. Damage to the generator transformer would be highly unlikely.
- The final outage duration to repair Unit C4 would depend on the level of damage to the shaft at the bearing locations, whether the HP and IP turbine rotor deformed permanently, and whether there was mechanical damage to the generator rotor.

7.7 Chapter Summary

This chapter examined the role played by the Unit C4 DC and AC systems during the execution of this switching sequence.

The next chapter explores how the collapse of the Unit C4 DC system voltage led to the loss of AC in the unit.

- The DC supply that controls the Unit C4 415 V AC switchgear is located on the Unit C4 distribution switchboard, and this would be restored if the automatic changeover switch successfully functioned.
- This means that when the emergency diesel generator activated and supplied the Station AC emergency switchboard, the Unit C4 AC switches could have been configured to route this AC supply to Unit C4 emergency switchboard.

However, the Unit C4 AC switches would have then likely disconnected the AC supply to the Unit C4 distribution switchboard, due to a design issue inherent in the design of the switches.

While this is discussed in detail in Appendix XX, this is evidenced by the following:

- When Calvale substation disconnected Callide C from the grid, Unit C3 lost AC supply.
- The Unit C3 AC switches were configured to route the supply from the Station emergency switchboard (which was supplied from the emergency diesel generator) to the Unit C3 emergency switchboard.
- The Unit C3 AC switches then disconnected this AC supply.

It is likely that the Unit C4 AC switches would have responded in a similar manner in this scenario.

8 HOW THE LOSS OF AC OCCURRED

8.1 Introduction

This chapter examines how the collapse of the Unit C4 DC voltage led to a loss of Unit C4 AC supply and how the loss of AC supply led to the loss of Unit C4 DC supply.

8.2 The Manner of the Collapse of the Unit C4 DC Voltage

Prior to the opening of the interconnector between the Unit C4 and Station DC systems, the voltage in the Unit C4 DC system was being maintained by Station. When the interconnector was opened, the Unit C4 battery charger became the unit's sole source of supply, and it was required to maintain the voltage level in the Unit C4 DC system, see Figure 95.

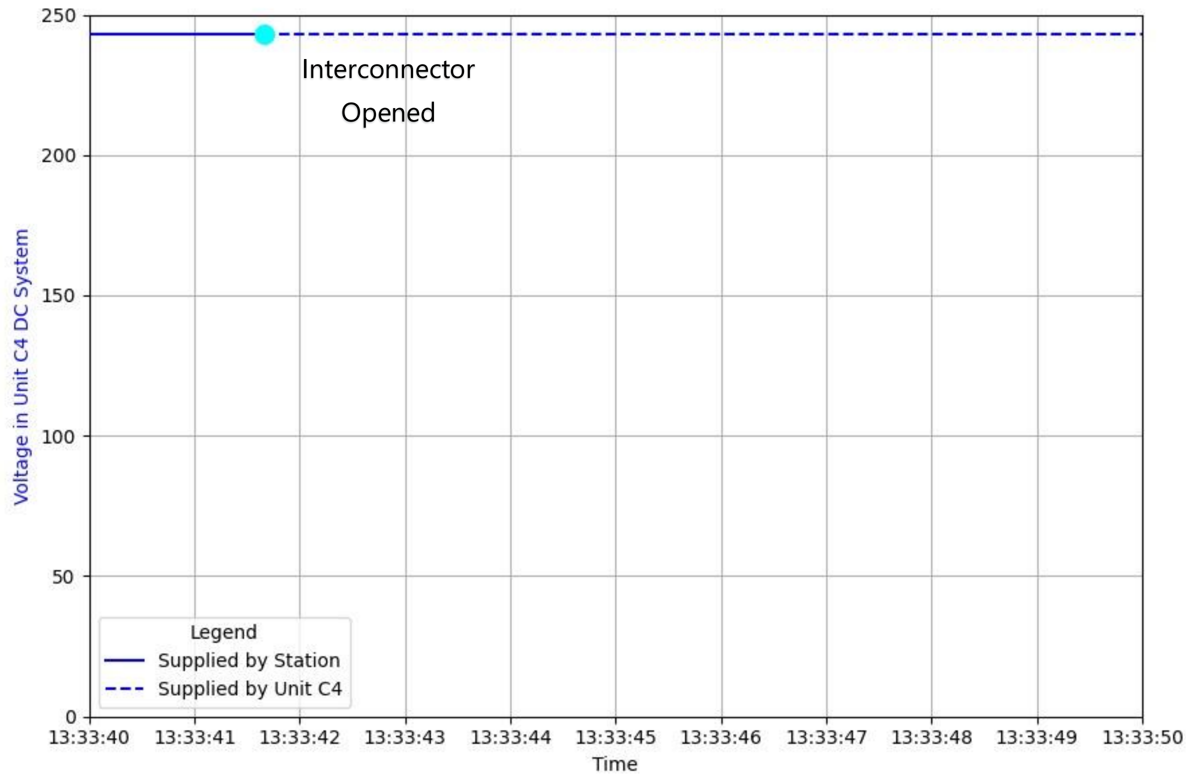


Figure 95 Required behaviour of Unit C4 battery charger (indicated by dashed line)

This did not occur - the voltage collapsed when the interconnector was opened, and it was the manner in which this collapse occurred that played a key role in the incident. Figure 96 shows the voltage in the Unit C4 DC system prior to and after the opening of the interconnector.[87]

[87] The dark blue dots depict the data as measured by the integrated control and monitoring system (ICMS) on the Unit C4 distribution switchboard.

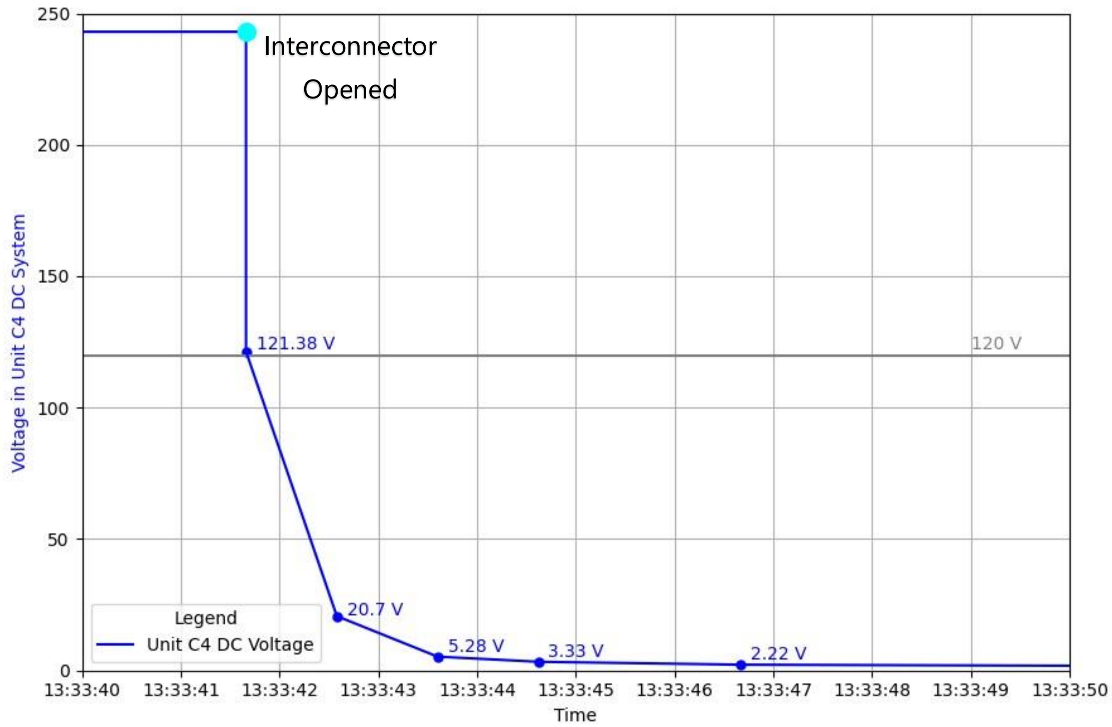


Figure 96 DC voltage in Unit C4 distribution switchboard

Prior to the interconnector opening, the voltage in the DC system was ~243 V. When the interconnector was opened, the voltage collapsed to ~120 V, then rapidly decayed to ~0 V.[88] This voltage collapse was a result of the behaviour of Unit C4 battery charger, which will be discussed in detail in Chapter 9.

The remainder of this chapter discusses how the manner in which the collapse occurred led to the loss of AC supply.

8.3 How the Unit C4 DC Voltage Collapse Led to the Loss of AC Supply

8.3.1 Introduction

The Unit C4 DC voltage collapse led directly to the loss of AC supply. The collapse resulted in a protection system referred to as 'arc flap protection' activating, which tripped the Unit C4 AC system. The sections that follow introduce the concepts of arc flap protection (and an electrical arc), and explain how this protection system erroneously activated and led to the loss of AC supply to Unit C4.

[88] The dark blue dots in Figure 96 are taken directly from the ICMS system. The light blue dot, however, was not recorded by the system. Rather, it has been included as a likely indicative value at the time immediately prior to the interconnector being opened.

8.3.2 Arc Flap Protection

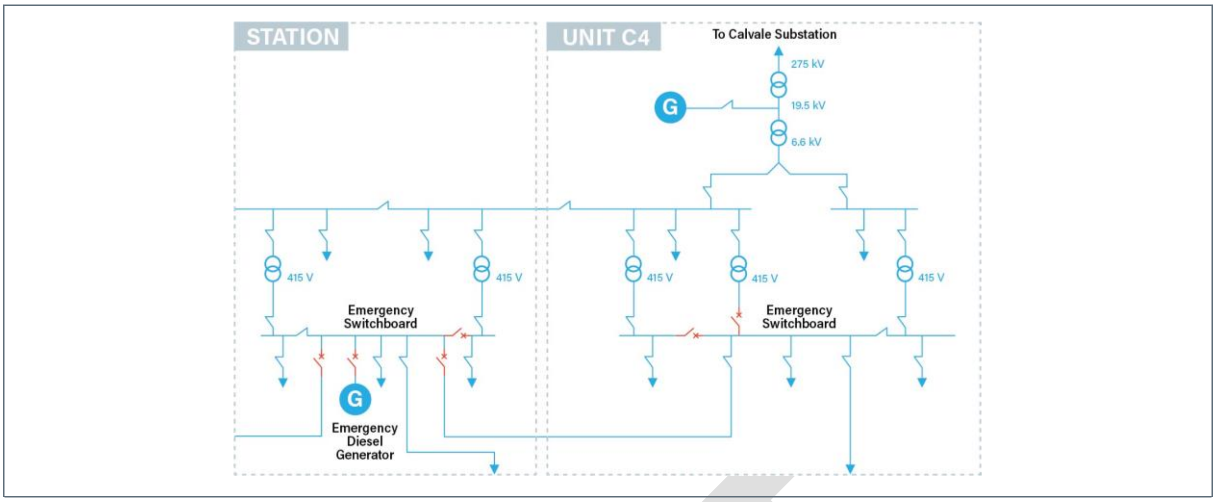
The occurrence of an electrical arc flash – an explosion caused by electricity passing through the air – is a major hazard in high-voltage AC electrical systems. When an electrical arc occurs, it is critical to disconnect supply to prevent continued arcing. In Callide C, the system used to detect and respond to arcing in 6.6 kV AC electrical cabinets is referred to as 'arc flap protection'.[89]

On the day of the incident, the arc flap protection system on the Unit C4 6.6 kV AC incomer circuit breaker cabinets operated and led to the loss of AC supply. This was an erroneous operation because no actual electrical arc flash occurred in these cabinets at the time.

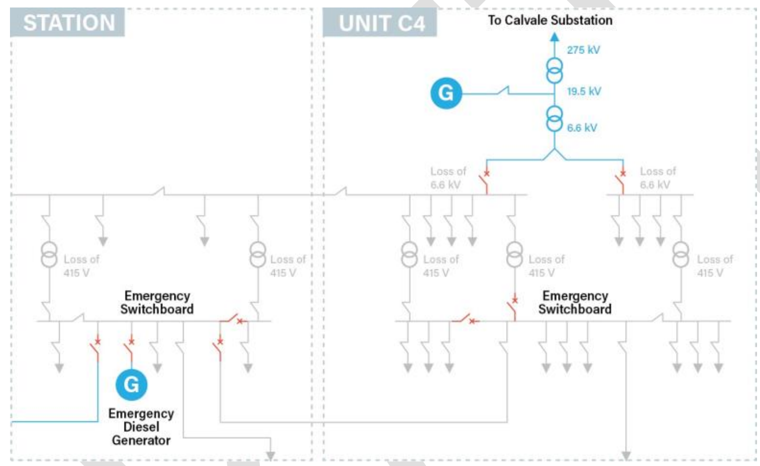
8.3.3 The Role of the 6.6 kV AC Incomer Circuit Breakers in the Unit C4 AC System

As discussed in Chapter 5, Unit C4 has two 6.6 kV AC incomer circuit breakers that connect the AC system to its source of supply – the Unit C4 generator. If these circuit breakers are closed, then AC supply is available to Unit C4. But if these circuit breakers open, the AC supply to Unit C4 is lost, see Figure 97.

[89] The term 'arc flap protection' is used within CS Energy (and in this report), rather than the more common industry term 'arc flash protection'. This is due to the specific implementation of arc flaps to detect the occurrence of an electrical arc flash.



(a) 6.6 kV incomer circuit breakers closed, connecting AC supply to Unit C4



(b) 6.6 kV incomer circuit breakers open, disconnecting AC supply to Unit C4

Figure 97 Unit C4 AC 6.6 kV incomer circuit breakers closed vs open

On the day of the incident, the arc flap protection operated and tripped the Unit C4 6.6 kV AC incomer circuit breakers, disconnecting the AC supply to the Unit C4 AC system. An explanation of how arc flap protection operates, and why it operated erroneously, is presented in the following sections.[90]

8.3.4 How Arc Flap Protection Works

If an electrical arc occurs inside one of the 6.6 kV incomer circuit breaker cabinets, it creates a pressure wave that pushes open a hinged flap on the top of the cabinet. An illustration of one of the 6.6 kV incomer circuit breaker cabinets, with the hinged flap, is shown in Figure 98.

[90] It is believed the same arc flap protection logic is fitted to all the 6.6 kV AC circuit breakers on the Unit and Station switchboards. Only the Unit C4 6.6 kV AC incomer circuit breaker cabinets were considered as part of this investigation. The other 6.6 kV AC circuit breakers did not play a relevant role in the incident.

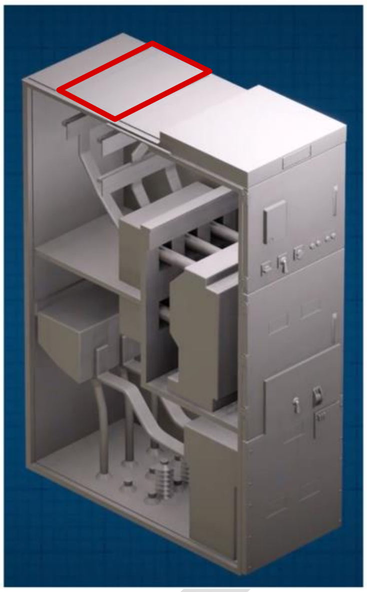


Figure 98 6.6 kV AC incomer circuit breaker cabinet with hinged arc flap indicated in red

A switch at the top of the cabinet is held closed (i.e., switched on) when the arc flap is in a closed position (i.e., there has been no pressure wave to open it). The DC system voltage is passed through this switch to a protection relay. Figure 99 shows the location of the switch and protection relay, with the DC system voltage depicted by the purple line.

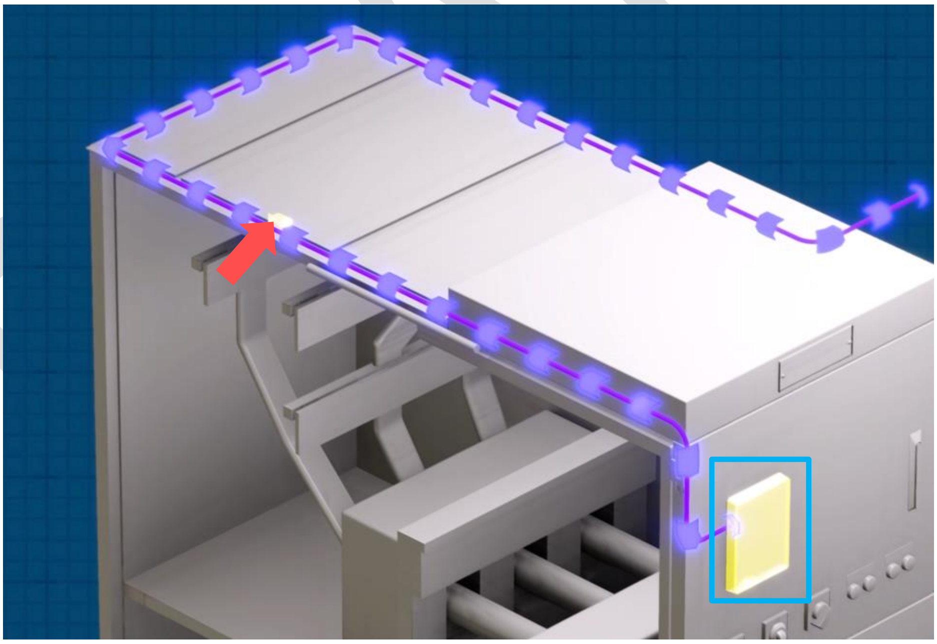


Figure 99 Location of switch (red arrow) and protection relay (blue square)

The protection relay monitors the voltage from the switch, and as long as the protection relay detects that the DC voltage is present, it takes no action. However, if an arc occurs and blows the arc flap open, this opens the switch, which collapses the DC voltage being monitored by the protection relay, as indicated by red arrows in Figure 100.

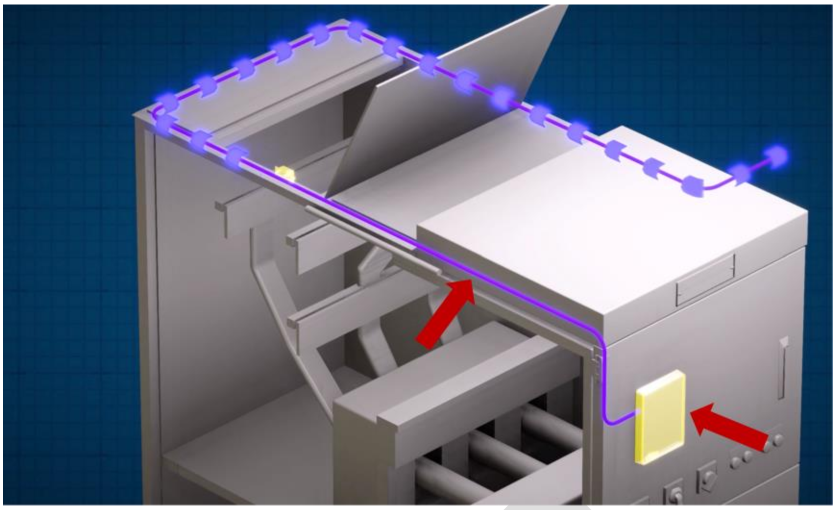


Figure 100 Arc flap opens, leading to opening of switch and collapse in DC voltage

When the protection relay detects that the voltage collapses (in this case, when it drops below 164 V)[91] this results in the relay responding as if an arc flash has occurred. It then sends a trip signal to the circuit breaker inside the cabinet, see Figure 101.

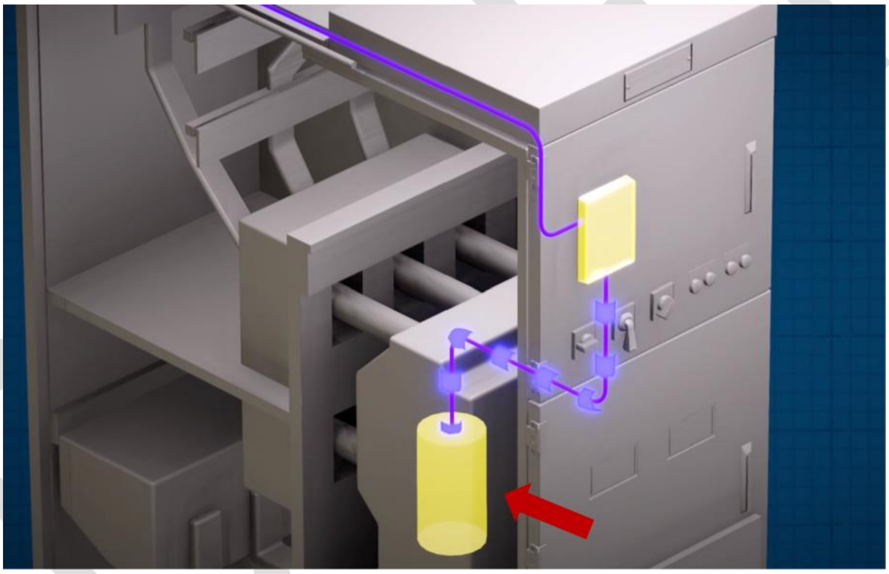


Figure 101 Protection relay sends trip signal to AC incomer circuit breaker (trip coil of circuit breaker indicated by red arrow)

When the circuit breaker receives the trip signal, it operates and disconnects the AC supply to prevent further arcing.

On the day of the incident, no arc flash occurred. Rather, when the Unit C4 DC system voltage collapsed to ~120 V, the protection relays detected that the voltage had fallen below 164 V, and responded by tripping the 6.6 kV AC incomer circuit breakers. In other words, the arc flap protection

[91] As measured by the Brady Heywood investigation.

could not distinguish between a voltage collapse caused by the arc flap protection switch opening, and the DC system voltage collapse that occurred in the incident.

8.3.5 Incomer Circuit Breakers Operate and Cause Loss of AC Supply

If the voltage had collapsed to below 101 V instead of collapsing to ~120 V, the protection relays would have been unable to successfully trip the AC incomer circuit breakers. (In order for the circuit breakers to successfully trip, their DC supply voltage needs to be at least 101 V.)[92]

The manner in which the Unit C4 DC supply collapsed, therefore, played a critical role in the loss of AC supply because:

- When the DC voltage collapsed to ~120 V, the protection relays interpreted that an arc *had occurred* and sent a trip signal to the circuit breakers.
- The circuit breakers operated and tripped the AC supply to Unit C4 *before* the DC voltage had sufficient time to further decay below 101 V.

While the voltage collapse from ~243 V to ~120 V was relatively instant, it took time for the voltage to decay to below 101 V.[93] Therefore, there was a window of time where the voltage was below 164 V (initiating the trip), but above 101 V (the minimum operating voltage for the circuit breaker to trip). This timeframe was of sufficient duration to successfully execute the trip, as illustrated in Figure 102.[94]

[92] This minimum voltage was determined by tests performed on the Unit C4 6.6 kV AC incomer circuit breakers as part of the Brady Heywood investigation.

[93] This time is determined by the capacitances, inductances and loads in the system.

[94] Data from the day of the incident shows that less than 100 milliseconds elapsed between the arc flap being detected by the protection relay (albeit erroneously) and the incomer circuit breaker being opened.

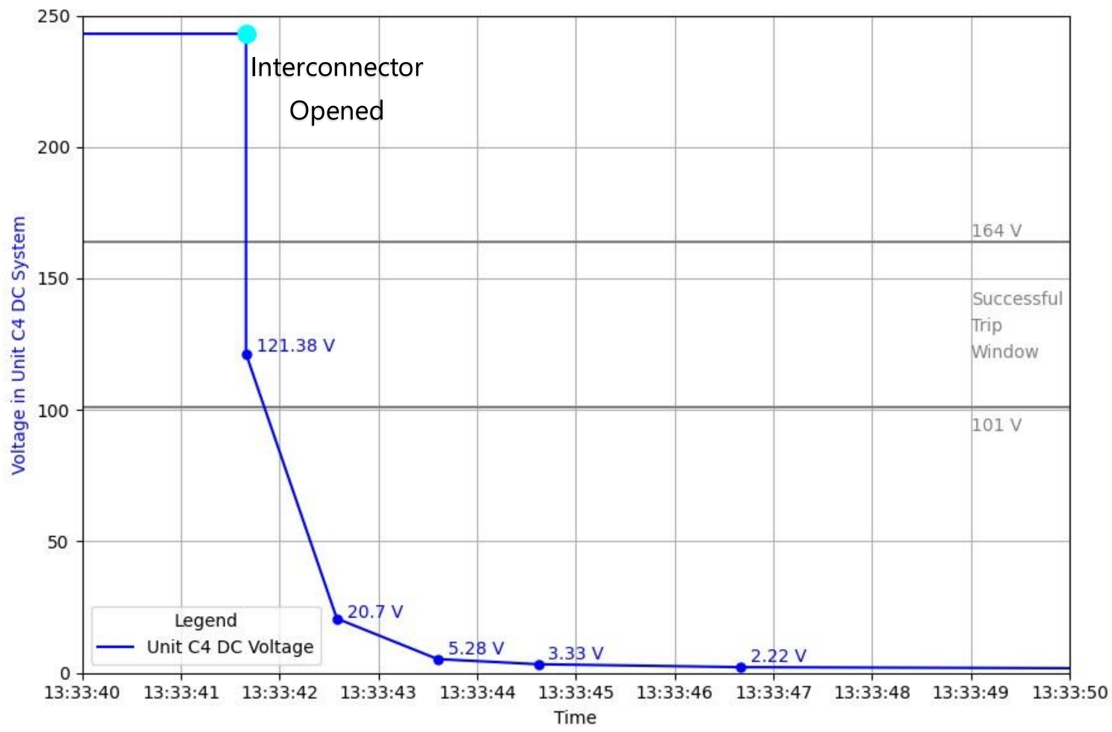


Figure 102 Trip window

When the 6.6 kV AC incomer circuit breakers tripped, all AC supply was lost to Unit C4 and Station, see Figure 103.

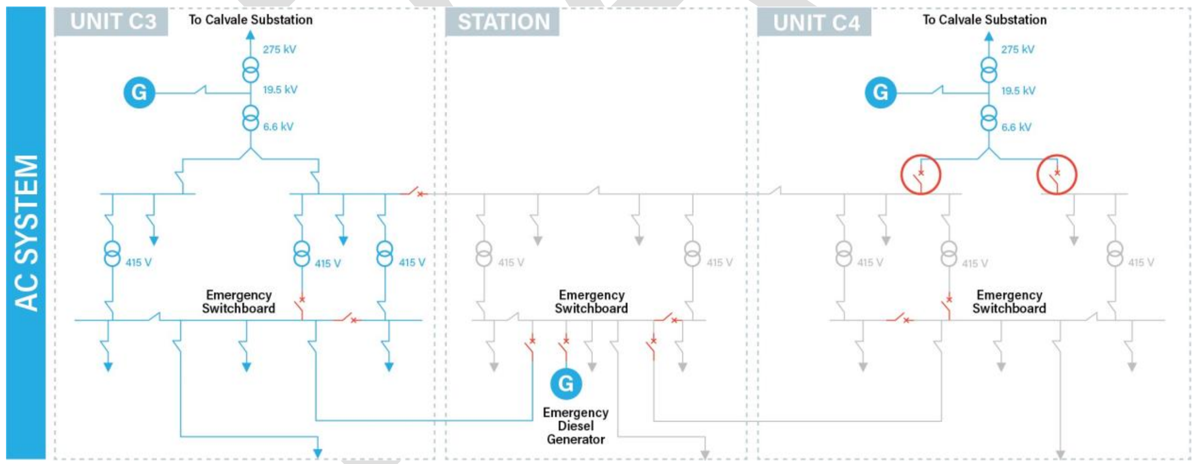


Figure 103 6.6 kV incomer circuit breakers tripping disconnected Unit C4 and Station AC supply

8.3.6 A Note on the Manner of the Collapse of DC Voltage

Had the manner of the DC voltage collapse been different, then different outcomes may have occurred. For example:

- Had the voltage collapsed, but stayed above 164 V, the protection relays would likely not have initiated a trip.

- Had the voltage collapsed below 101 V, the protection relays would likely have still initiated a trip (because the voltage was below 164 V), but the 6.6 kV AC incomer circuit breakers would not have tripped because the DC voltage was below 101 V and too low for them to operate.[95]
- Had the voltage collapsed below 80 V, the protection relays would have likely shut down due to a lack of supply and would likely not have initiated a trip.[96]

8.4 How the Loss of AC Supply Led to the Loss of DC Supply

8.4.1 Battery Charger Shuts Down and DC Supply is Lost

The trip of the 6.6kV AC incomer circuit breakers resulted in a complete loss of AC supply to the Unit C4 AC system, including the AC supply to the Unit C4 battery charger, see Figure 104.

[95] In this scenario, the AC supply may still have been lost: the initial collapse in DC voltage to below 101 V results in there being insufficient voltage to operate the AC incomer circuit breakers and they remain closed. Therefore, the battery charger does not shut down, because it still has AC supply. With no loss of AC supply, the battery charger then detects that the voltage in the DC system is low, and responds by increasing it. But as the voltage begins to recover, it passes up through the trip window of 101 V to 164 V, causing the AC incomer circuit breakers to trip (on the way up), leading to a loss of AC supply.

[96] In this scenario, the AC supply could still have been lost by the same mechanism discussed in the footnote above, provided the protection relay had powered up while the recovering voltage was still within the trip window.

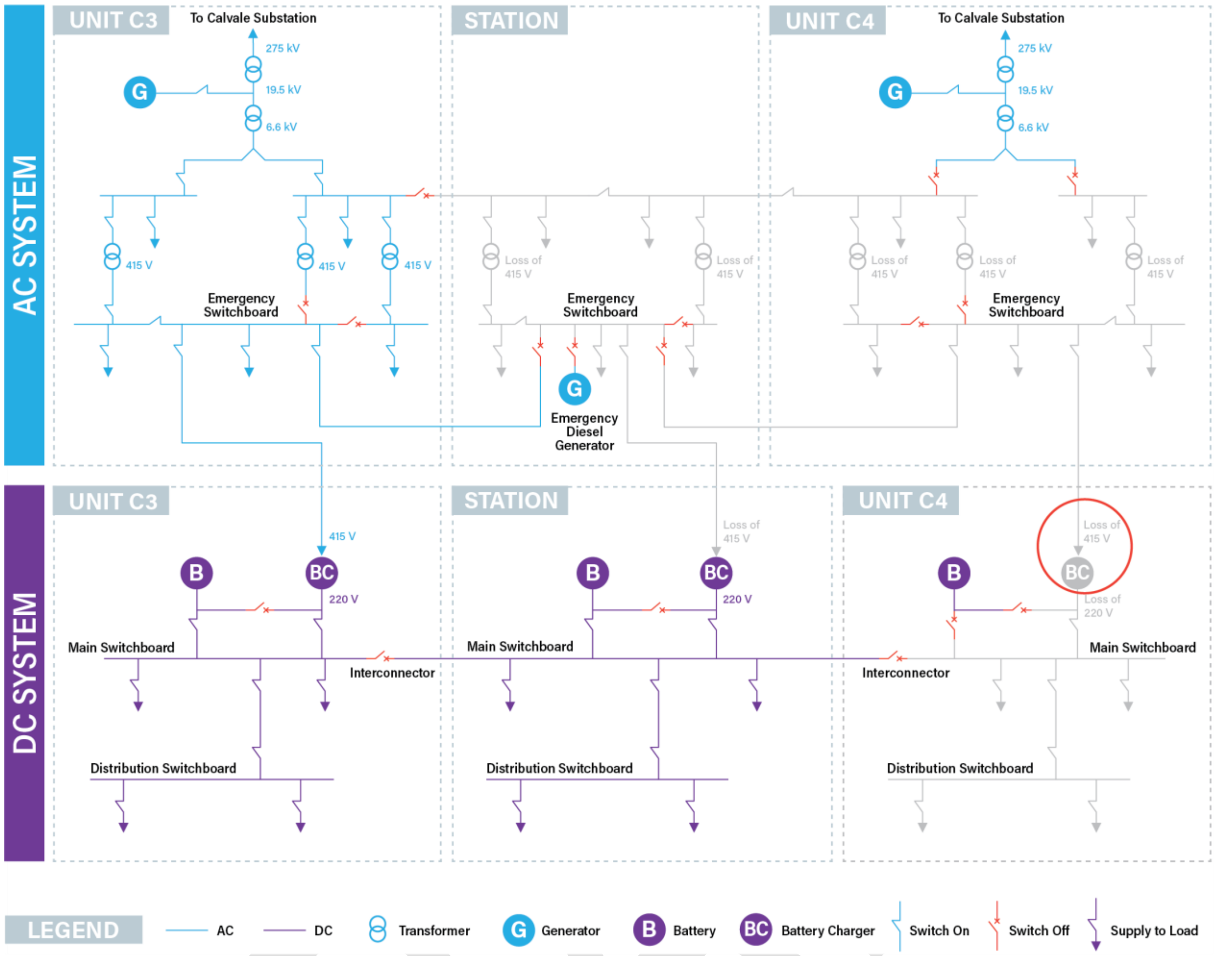


Figure 104 Opening of 6.6 kV incomer circuit breakers causes loss of AC supply to Unit C4 battery charger (indicated in red)

Had the AC supply to the Unit C4 battery charger not been lost, it would have likely responded to the collapse in DC voltage and restored the system voltage to its usual level within 2 seconds.[97] However, with no AC supply, the Unit C4 battery charger shut down, leading to a complete loss of DC supply to Unit C4.

8.5 Chapter Summary

This chapter explored how the collapse of DC voltage resulted in the protection relays in the 6.6 kV AC incomer circuit breakers responding as if an arc had occurred, which resulted in the protection relays initiating a trip of the 6.6 kV AC supply to Unit C4.

The tripping of the 6.6 kV AC incomer breakers resulted in a loss of AC supply to Unit C4 and Station, including a loss of the 415 V AC supply to the Unit C4 battery charger.

[97] The investigation concluded that the Unit C4 battery charger would have likely recovered and restored the voltage to ~243 V within two seconds, as discussed further in Chapter 9 and in Appendix A4.

With no AC supply, the Unit C4 battery charger shut down. Because the Unit C4 battery charger was the sole source of supply to the Unit C4 DC system at this time, this led to a loss of DC supply to Unit C4.

The next chapter examines how the behaviour of the Unit C4 battery charger contributed to the collapse in the Unit C4 DC system voltage.

9 THE ROLE OF THE UNIT C4 BATTERY CHARGER IN THE INCIDENT

9.1 Introduction

The Unit C4 battery charger played a key role in the incident. Specifically, it failed to maintain the voltage level in the Unit C4 DC system despite the switching sequence requiring it to do so.

This chapter explains the technical history of the Unit C4 battery charger, how it operates, and the significance of its behaviour during the switching sequence taking place on the day of the incident.

9.2 The History of Unit C4 Battery Charger

In the 18 months leading up to the incident, an upgrade program had been initiated to replace the battery chargers at Unit C3, Station and Unit C4. During this period, the battery chargers in Unit C3 and Station were replaced and successfully connected to their corresponding DC systems.

By 25 May of 2021, the Unit C4 battery charger had been replaced and was ready to be connected to Unit C4 DC system. It was during this connection process that the incident occurred.

9.3 General Behaviour of the Unit C4 Battery Charger

9.3.1 Introduction

This section provides a simplified introduction to how the Unit C4 battery charger operates, specifically focusing on its operation relevant to the incident.[98]

9.3.2 Principles of Unit C4 Battery Charger Operation

In simple terms, the Unit C4 battery charger is a voltage conversion device, i.e., it takes in an AC voltage and outputs a DC voltage at a specific level.

When the Unit C4 battery charger is connected to a system, such as the Unit C4 DC system, it will maintain the voltage in the system at this specific level, i.e., any battery connected to the system will be charged to this level, and any loads connected will be supplied by the battery charger.

In this report, the specific level that the battery charger maintains the system voltage at is referred to as the battery charger's 'target output voltage'.[99]

While the battery charger can be considered a *voltage* conversion device, it operates by continually measuring the voltage in the system that it is connected to and adjusting its output *power* accordingly. The following two sections explain how the battery charger achieves this.

[98] The simplified explanation presented in this report is intended to convey the complexities of the operating principles of the Unit C4 battery charger to the non-technically trained reader. As such, some elements of the battery charger's behaviour have been greatly simplified for clarity. A more detailed discussion of the operation of the battery charger is presented in Appendix A4.

[99] The Unit C4 battery charger had been configured with a target output voltage of 245.16 V.

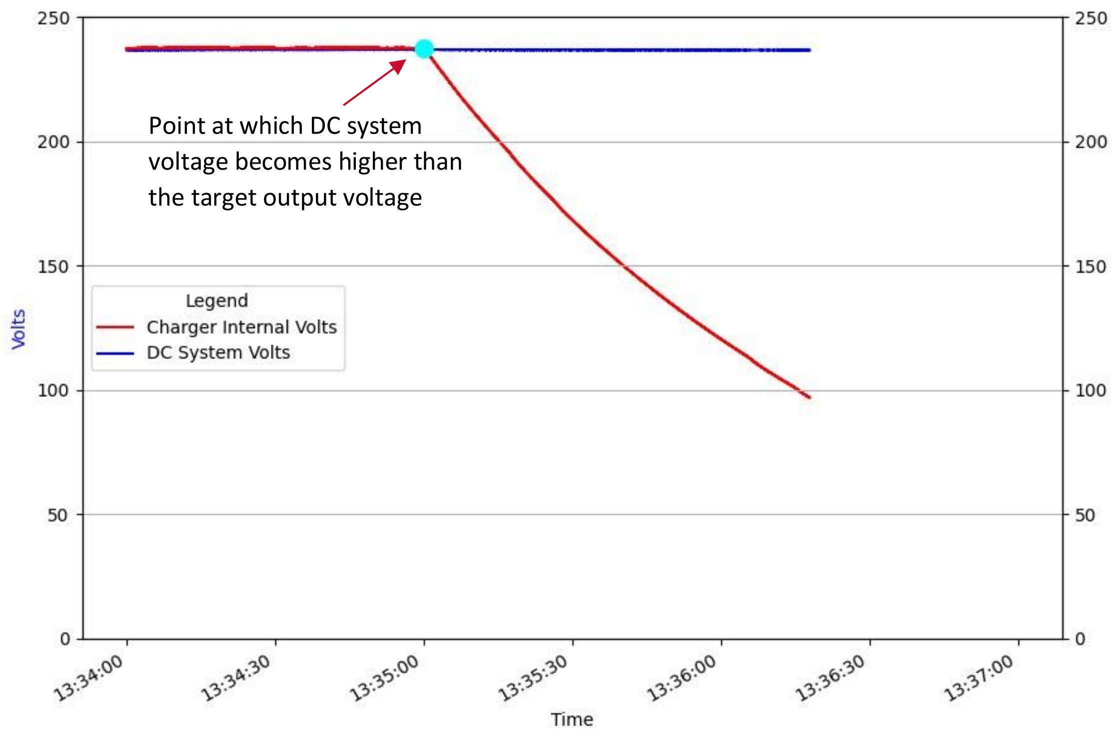
9.3.3 Behaviour of the Battery Charger When the System Voltage is Lower Than its Target Output Voltage

When the battery charger measures that the system voltage is *lower* than its target output voltage, it responds by *increasing* its output power, which *increases* the voltage in the system.

9.3.4 Behaviour of the Battery Charger When the System Voltage is Higher Than its Target Output Voltage

When the battery charger measures that the system voltage is *higher* than its target output voltage, it responds by *decreasing* its output power, which *decreases* the voltage in the system.

If, however, there is another source of supply that is maintaining the voltage in the DC system at this higher level (such as another battery charger or a battery), the battery charger measures that the voltage in the system remains higher than its target and stops producing power. When this happens, the voltage inside the Unit C4 battery charger gradually decays.[100] This gradual decay of the internal voltage was demonstrated by testing performed as part of the Brady Heywood investigation and is illustrated in Figure 105.[101]



[100] This complex behaviour of the Unit C4 battery charger was identified as part of the investigation, and is a behaviour specific to the battery chargers used in Callide C. The reason that the internal voltage decays gradually (rather than instantly dropping to zero when the battery charger's output power drops to zero), despite the battery charger no longer producing power, is because the internal voltage is maintained by capacitors inside the battery charger. It is the gradual discharging of these internal capacitors that leads to the gradual decay of the battery charger internal voltage. The capacitors are not maintained at the system voltage due to a diode between the capacitors and the output of the battery charger.

[101] The data used in this figure was obtained by measuring the Unit C4 battery charger's internal voltage, and decreasing the target output voltage of the Unit C4 battery charger while it was connected to a fully charged battery.

Figure 105 Battery charger internal voltage decays when the system voltage is higher than its target output voltage

The dark blue line depicts the voltage in the system (which is maintained by another battery charger or battery at a higher level), and the red line illustrates the decay of the battery charger's internal voltage.

9.3.5 How the Battery Charger Responds When it Becomes the Sole Source of Supply in a System

If at any point in time this other source of supply (such as another battery charger or a battery) that is maintaining the DC system voltage at the higher level is suddenly removed, the Unit C4 battery charger becomes the sole source of supply to the DC system.

In this scenario, when the other source of supply is removed, the voltage in the system suddenly *drops* to match the internal voltage of the battery charger. This drop in voltage was demonstrated by testing performed as part of the Brady Heywood investigation and is depicted in Figure 106 by the dark blue line.[102]

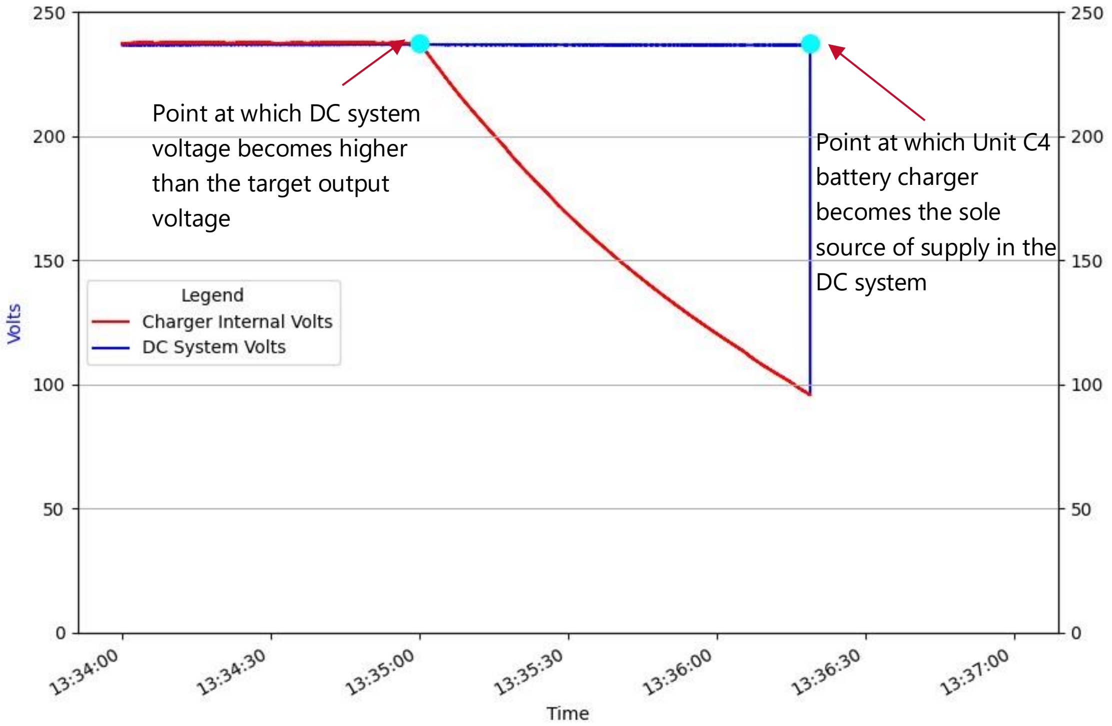


Figure 106 Voltage at the output of the battery charger collapses to the level of the battery charger's internal voltage

In other words, the voltage of the DC system will collapse to the battery charger's internal voltage. The Unit C4 battery charger then detects that the voltage in the system is *lower* than its target output voltage, and responds by *increasing* its output power. This results in the battery charger restoring the voltage in the system in accordance with its target output voltage.

[102] DATA SOURCES LEGEND

This restoration of voltage has been demonstrated through Brady Heywood testing to take between several hundred milliseconds to two seconds, and is depicted in Figure 107.[103] (Note the voltage collapse and recovery lines are almost superimposed on one another).

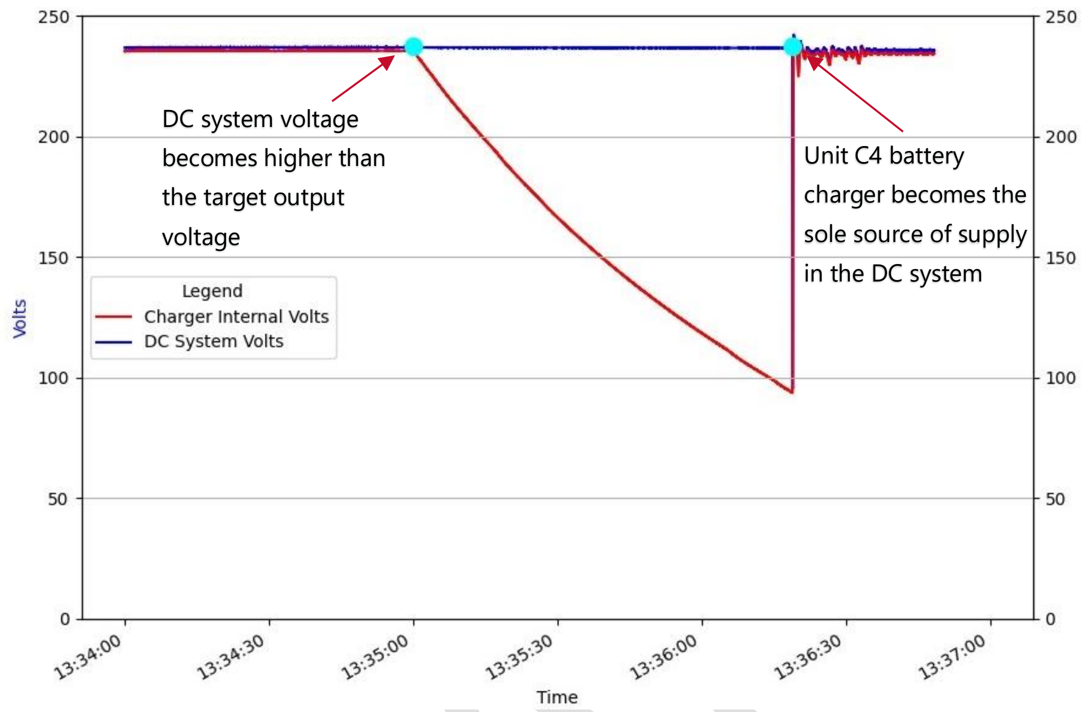


Figure 107 Battery charger recovers DC system voltage

A close-up of the recovery of the voltage is shown in Figure 108, where the battery charger took ~35 milliseconds to respond to the decrease in voltage, and an additional ~140 milliseconds to restore the system voltage to ~240 V.

103 The response time of the battery charger is discussed further in Appendix A4.

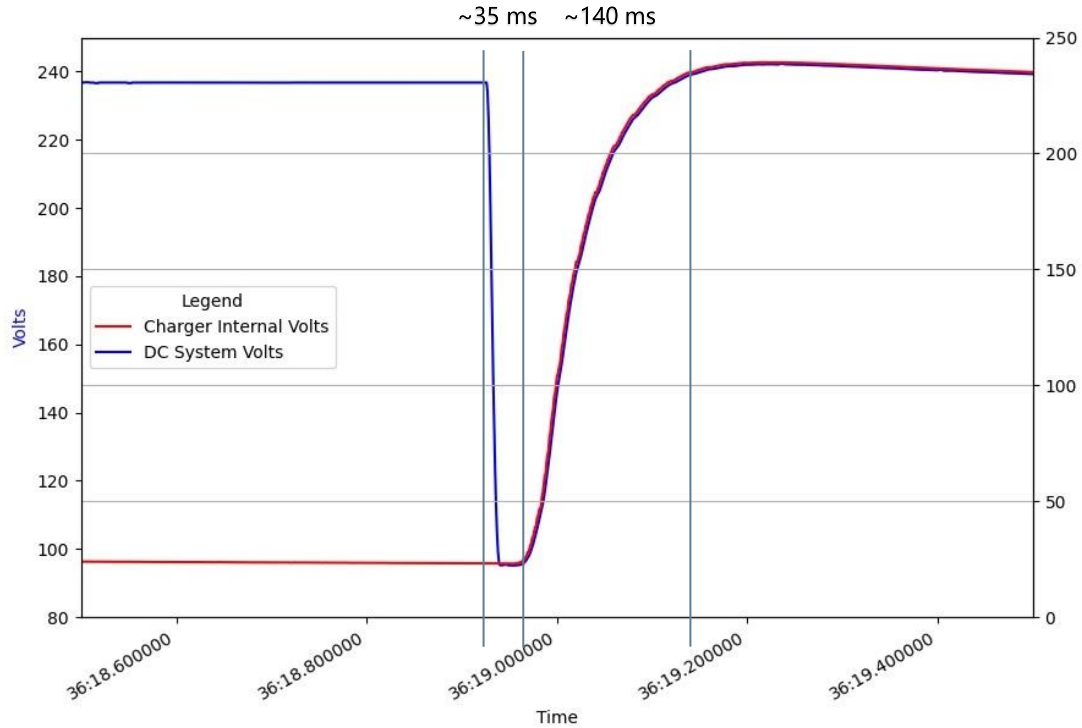


Figure 108 Close up of collapse then recovery of battery charger external voltage

It is this specific demonstrated behaviour of the Unit C4 battery charger that is crucial to understanding its response on the day of the incident.

9.4 Connecting the Unit C4 Battery Charger to the DC System

The initiating event for the incident occurred during the switching sequence to connect the Unit C4 battery charger into the DC system. Prior to this part of the process, the battery had been successfully charged overnight by directly connecting it to the battery charger. The key steps to connect the Unit C4 battery charger were:

(a) Connect the Unit C4 battery charger to the Unit C4 DC system.

(b) Disconnect the Station DC system from the Unit C4 DC system.

These steps in the switching sequence were carried out by operating the two switches indicated in red in Figure 109.

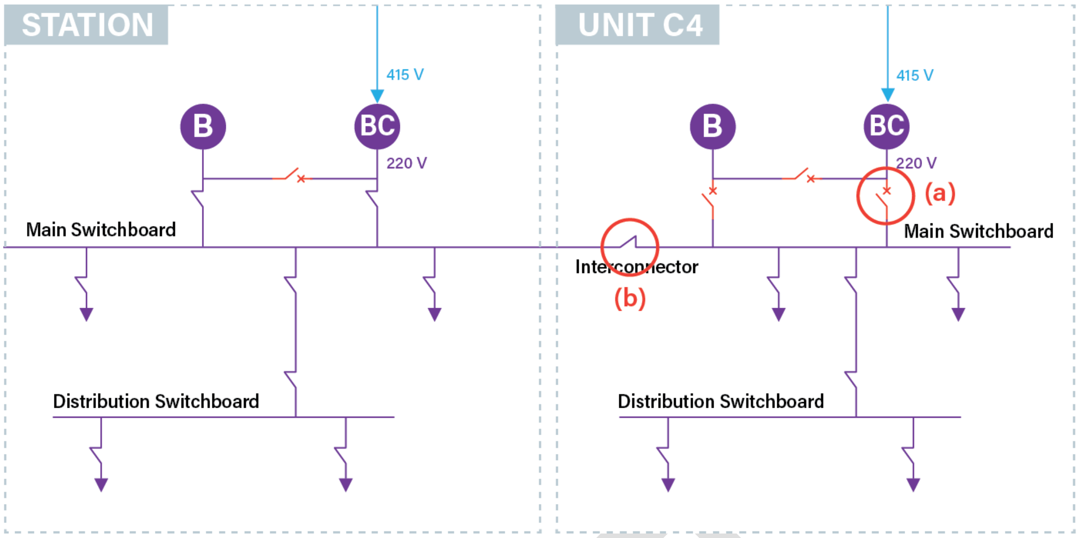


Figure 109 Steps in switching sequence to connect Unit C4 battery charger

On the day of the incident, the Unit C4 battery charger was connected to the DC system by closing the switch at location (a). Then 74 seconds later, the interconnector at location (b) was opened to disconnect the Station and Unit C4 DC systems.

The next two sections consider the status of the DC system before and after these steps in the switching sequence.

9.4.1 State of the DC System Prior to Connecting Unit C4 Battery Charger

Prior to connecting the Unit C4 battery charger, the DC system was being supplied by the Station battery charger, which had been configured with a target output voltage of 243 V.[104] This meant that the Station battery charger was:

- Supplying power to all the loads in the Station and Unit C4 DC systems.
- Maintaining the voltage in the DC system at ~243 V.
- Maintaining the Station battery at a full state of charge (~243 V).

This is shown in Figure 110.

[104] There is no evidence that indicates that the difference in the configured target output voltage of the Station battery (243 V) charger was intentionally configured to be different than the Unit C4 battery charger (245.16 V).

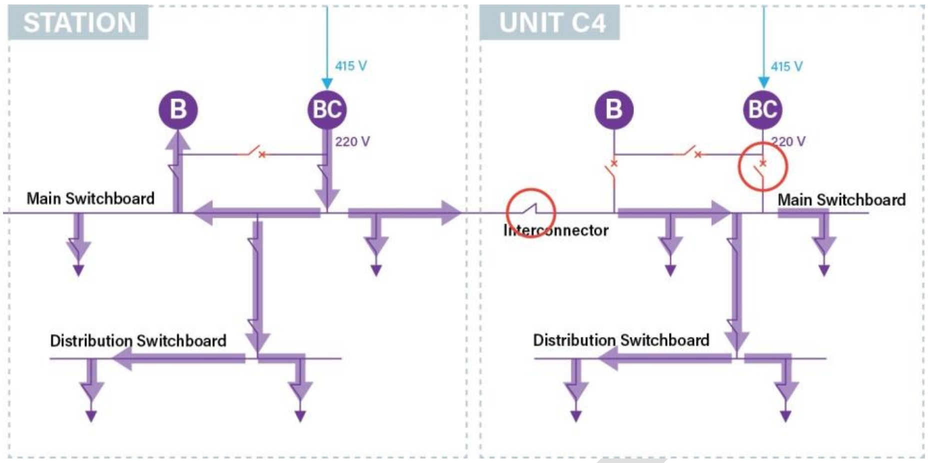


Figure 110 Station battery charger supplies the DC system

9.4.2 State of the DC System After Connecting the Unit C4 Battery Charger

After connecting the Unit C4 battery charger, there was no observable change in the DC system.

The Station battery charger:

- Continued to supply all the loads in the DC system. (i.e., it did not decrease its output power.)
- Continued to maintain the voltage in the DC system at ~243 V.

The Unit C4 battery charger:

- Did not increase its output power.
- Did not increase the voltage in the DC system.

This indicates that the voltage in the DC system (~243 V) was *higher* than the target output voltage of the Unit C4 battery charger.[105,106,107] As discussed earlier in this chapter, when this occurs, the Unit C4 battery charger stops producing power and its internal voltage gradually decays.

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[105] This occurred despite the Unit C4 battery charger being configured to output 245.16 V.

[106] If the voltage in the DC system had been *lower* than the Unit C4 battery charger's target output voltage, the Unit C4 battery charger would have responded by increasing its output power, supplying the loads in the DC system, increasing the voltage in the DC system in accordance with this (higher) target output voltage, and charging the Station battery to this higher level. The Station battery charger would have responded by decreasing its output power to zero. As discussed, this did not occur.

[107] From the instant the Unit C4 battery charger was connected to the DC system, it behaved in a manner consistent with what would be expected if the voltage in the system was higher than its target output voltage. Despite this, the target output voltage of the Unit C4 battery charger had been configured to 245.16 V, and the voltage in the DC system was ~243 V.

As discussed in section 0, if the Unit C4 battery charger's target output voltage had actually been 245.16 V when it was connected to the DC system, it would have raised the voltage in the DC system to ~245.16 V – and in doing so supplied power to any connected loads, and charged the Station battery to this level. This did not occur.

The most likely reason for this behaviour is because the Unit C4 battery charger had a feature enabled called 'temperature compensation'. (Temperature compensation was not enabled on the Station and Unit C3 battery chargers.) Temperature compensation is a feature found on most battery chargers that adjusts the battery charger's target output voltage based on the temperature of the battery.

It is, therefore, likely that the Unit C4 battery charger's internal voltage began to decay the instant the Unit C4 battery charger was connected to the Unit C4 main switchboard.[108]

Subsequent onsite testing indicates that on the day of the incident, in the 74-second period between being connected to the Unit C4 DC system and the opening of the interconnector, the battery charger's internal voltage would have likely decayed to ~120 V. Figure 111Figure 111 illustrates the hypothesised behaviour of the Unit C4 battery charger after it was connected.[109]

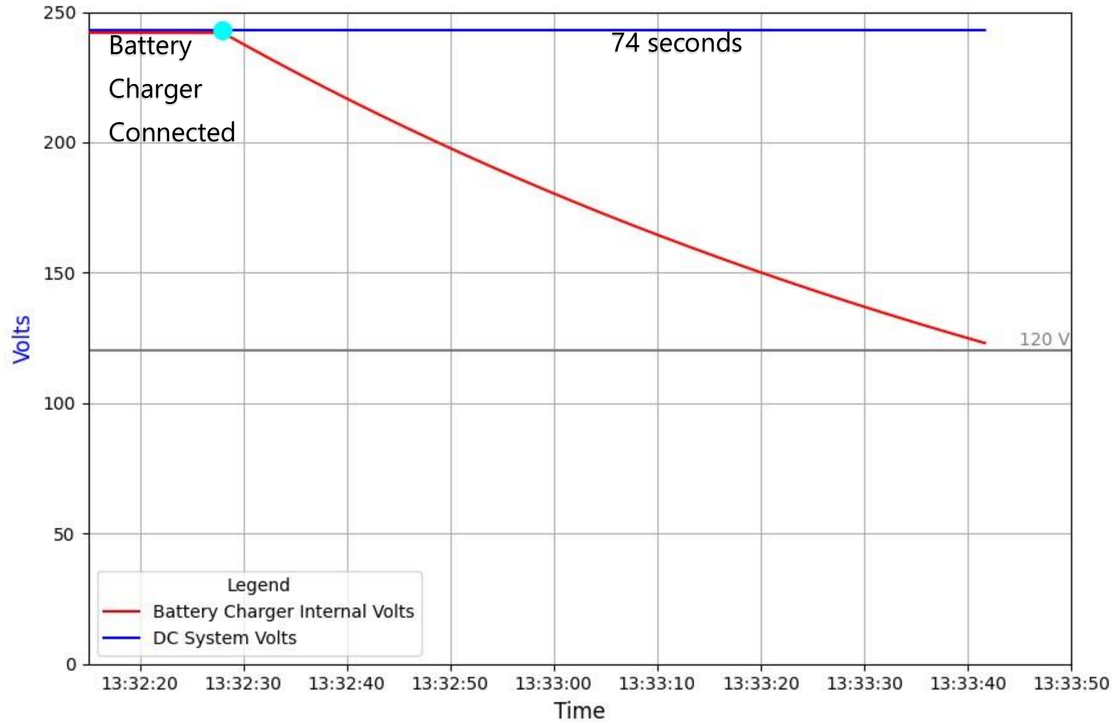

Figure 111 Likely decay of Unit C4 internal voltage to ~120 V

The Brady Heywood investigation determined that when temperature compensation is enabled on the Unit C4 battery charger, step changes of several volts in target output voltage occurred – despite there being no corresponding change in battery temperature. It was also demonstrated that the temperature compensation adjusted the target output voltage nearly six times more than expected. (For example, a simulated six degree change in temperature on the Station battery charger resulted in ~2 V change in its the configured output voltage, whereas the same simulated change on the Unit C4 battery charger resulted in a change if ~12 V change).

The target output voltage of the Unit C4 battery charger, along with the behaviour of temperature compensation, is discussed in detail in Appendix A4.

[108] It has been demonstrated that the gradual decay in voltage commences when the voltage measured by the battery charger is greater than its target output voltage. Prior to connecting the Unit C4 battery charger to the DC system, it is expected that the battery charger would have been providing a DC voltage at its output in accordance with its target output voltage.

[109] This has been determined both experimentally and through calculations. When the output of the battery charger reduces to zero, the internal voltage has been demonstrated to decay in accordance with an RC decay curve based on the on a parallel RC circuit comprising of bleed resistors in parallel with the internal capacitors.

9.4.3 State of the DC System after Opening of the Interconnector

CS Energy data from the day of the incident shows that at the time the interconnector was likely opened, the voltage in the Unit C4 DC system suddenly collapsed from ~243 V to ~120 V.[110] As discussed previously, ~120 V correlates with the likely internal voltage that the Unit C4 battery charger would have decayed to in this 74-second period, see Figure 112.

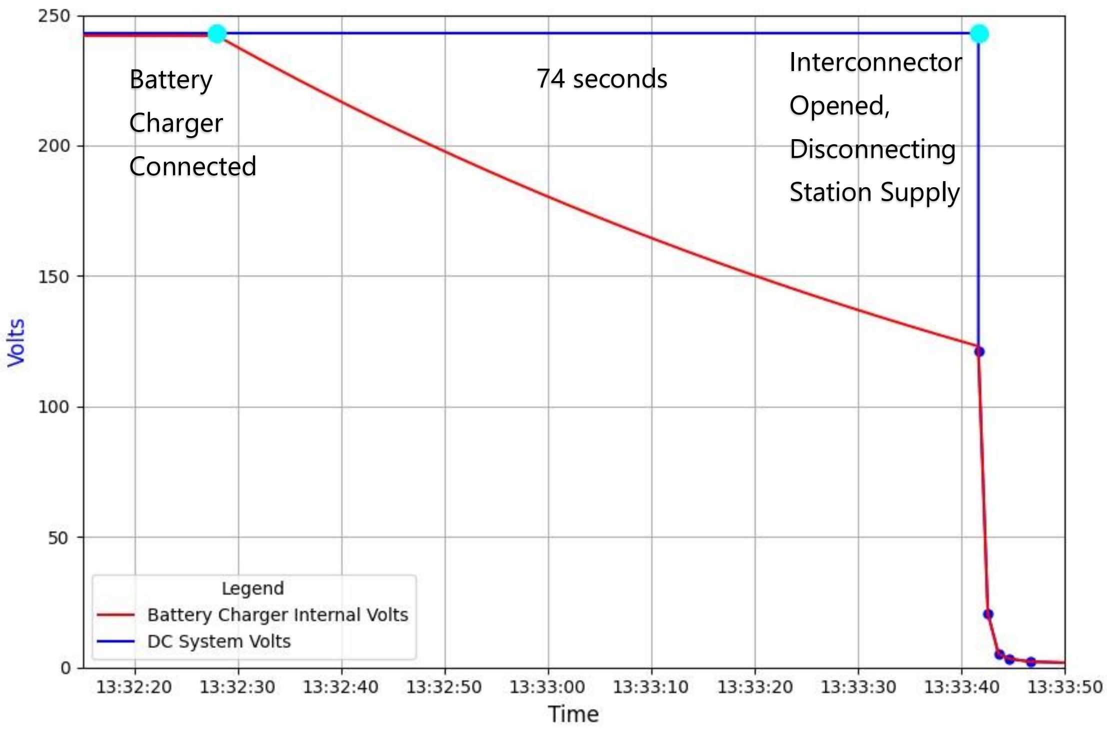

Figure 112 Likely collapse of DC system voltage to level of Unit C4 internal voltage (~120 V)

While the internal voltage on the day of the incident (red line) can only be hypothesised, the dark blue dots in Figure 112 and Figure 113 are taken from CS Energy supplied data of the voltage readings on the Unit C4 distribution switchboard. This data shows that after an initial collapse to ~120 V, the voltage in the DC system continued to decay rapidly. This decay is shown in greater detail in Figure 113.

[110] The exact time that the that the interconnector was opened was not captured by the ICMS system, but this time has been established by other means, and is discussed further in Appendix A3 (Electrical appendix)

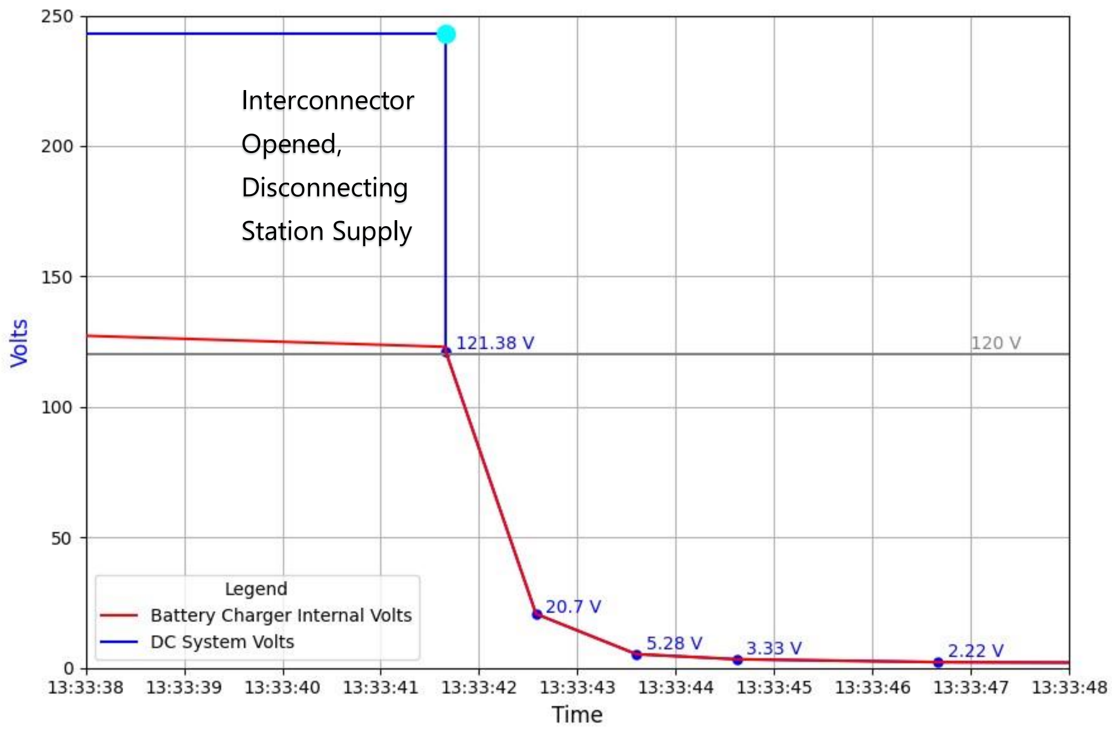

Figure 113 Zoom in of the likely collapse and decay of Unit C4 DC voltage

This data shows the voltage in the DC system collapsing to ~120 V, then rapidly decaying (dropping to ~5 V within 2 seconds).[111,112]

9.4.4 Impact of the C4 Battery Charger's Behaviour on the DC System

As discussed earlier in this chapter, when the battery charger detects that the voltage in the system is lower than its target output voltage, it responds by increasing its output power, and restoring the voltage in the system. On the day of the incident, the battery charger did not recover the voltage in the DC system, and the voltage rapidly decayed.

The battery charger did not recover the voltage because the voltage collapse led to the loss of the AC supply in Unit C4, and because the battery charger was supplied by the Unit C4 AC system, the battery charger shut down before it could recover the DC voltage.

[111] Data from the Unit C4 main switchboard shows a similar drop to ~110 V, then a decay at a similar rate. While the voltage levels measured by the ICMS is discussed further in Appendix A4, the technicalities of how the ICMS measures and stores analogue signals is outside the scope of this report.

[112] The reason the DC voltage decayed rather than dropped to zero volts immediately is because of the capacitors inside the charger. Any remaining load in the Unit C4 DC system discharged these internal capacitors rapidly, and the voltage in the DC system decayed to zero.

Had the AC supply to Unit C4 battery charger not been lost, it would have likely responded to this drop in voltage and recovered the voltage in the DC system within 2 seconds.[113] However, the loss of AC supply occurred before this recovery could occur.[114]

9.5 Chapter Summary

From the instant that the Unit C4 battery charger was connected to the DC system, it behaved in a manner consistent with the voltage in the system being higher than the battery charger's target output voltage. This conclusion is based the demonstrated behaviour of the Unit C4 battery charger in various tests conducted throughout the investigation, and a review of the available data on the day of the incident.

[113] The Brady Heywood investigation concluded that if the AC supply had not been lost, the Unit C4 battery charger would have likely recovered and restored the voltage to ~243 V in the order of several hundred milliseconds to 2 seconds, as discussed in Appendix A4.

[114] The battery charger was not capable of preventing the collapse in voltage, because it operates by first measuring that the voltage in the system is lower than its target output voltage, then responding by increasing its output. However, the opening of the interconnector resulted in an almost instantaneous collapse in voltage, and the battery charger was not able to respond fast enough to halt this collapse. It was also not able to respond fast enough and restore the DC voltage before the arc flap protection operated, disconnecting the AC supply to Unit C4 (including the AC supply to the Unit C4 battery charger).

10 TECHNICAL CONCLUSIONS

10.1 Key Causative Technical Events

The key causative technical events of the incident are summarised as follows:

- On the day of the incident, a replacement battery charger for Unit C4 DC system had been commissioned and was being connected to Unit C4.
- During the connection process, there was a collapse of voltage in Unit C4 DC system. The replacement Unit C4 battery charger was required to maintain the voltage in Unit C4 DC system but failed to do so.
- The collapse of voltage in Unit C4 DC system directly led to the loss of AC supply to Unit C4.
- The loss of AC supply to Unit C4 then directly led to the complete loss of the DC supply to Unit C4.
- The automatic changeover switch, which was designed to automatically restore DC supply to parts of Unit C4 DC system, was not functional and could not automatically restore DC supply to Unit C4. Had the automatic changeover switch worked, it could have altered the severity of the incident, although major component replacements are still possible under this scenario.

10.2 Key Consequential Technical Events

The loss of both Unit C4 DC supply and Unit C4 AC supply directly led to the destruction of the turbine generator in the following manner:

- With a loss of both AC supply and DC supply, the pumps required for the safe operation of the turbine generator were unavailable (e.g., lubrication oil pumps, seal oil pumps and cooling system pumps).
- With the loss of DC supply, Unit C4 lost its ability to disconnect from the grid and shut down safely.
- With the loss of AC supply, the valves controlling the flow of steam to the turbine were closed, preventing further steam from entering and driving the turbine.
- As the turbine generator was no longer being driven by steam, but was still connected to the grid, it went from generating electricity, to consuming electricity (i.e., motoring). This resulted in the turbine generator continuing to spin. This continued motoring, over a 34-minute period, in combination with the loss of critical systems, such as lubrication oil pumps, directly led to the destruction of the turbine generator.
- The motoring culminated in large components of the turbine generator (e.g., a two-tonne section of rotor) being ejected from Unit C4 in a turbine missile event.
- The generator remained connected to the grid for around 40 seconds after the turbine missile event. Following the turbine missile event, an electrical fault developed in the generator which led to arcing and caused almost three times its rated power to be drawn from the grid. This was detected at Calvale substation, which disconnected the Substation from the wider grid, hence disconnecting Unit C4. This initiated the destabilisation of the Queensland power grid.

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Brady Heywood.

Part B: Organisational Investigation

11 OVERVIEW OF PART B: ORGANISATIONAL INVESTIGATION

[Chapters 11-21 included separately]

The following key events occurred in the incident:

(a) **Collapse and loss of DC supply**:[115] There was a collapse in voltage and a subsequent loss of DC supply to Unit C4. This led to a loss of protection to the unit, which resulted in it being unable to shut down safely or disconnect from the grid.

(b) **Loss of AC supply**: The precise manner in which the DC collapsed led directly to a loss of AC supply to the unit. This led to a loss of the seal oil and lubrication oil. The shaft and bearings were now grinding metal-on-metal, resulting in friction, heat and damage. The loss of AC supply also caused the steam valves of the turbine to close, which meant it was no longer being driven by steam.

(c) **Motoring**: With Unit C4 no longer driven by steam, but still connected to the grid, it began 'motoring'. Motoring is when a unit goes from exporting power to importing power, which results in its generator operating as an electric motor. This causes the generator rotor to continue to spin and drive the turbine.[116]

(d) **Catastrophic failure**: After 34 minutes of sustained motoring, without lubrication oil and seal oil, the shaft tore apart at nine locations. Large segments were ejected from the unit in what is referred to as the 'turbine missile event'. The generator remained connected to the grid for the next 40 seconds, causing an electrical fault that led to Calvale substation disconnecting from the grid, which disconnected Unit C4.[117] The turbine missile event and electrical fault catastrophically destroyed the turbine, the generator, and the generator transformer.

[115] In the incident, the Unit C4 DC voltage collapsed from ~243 V to ~120 V. It then rapidly decayed to ~0 V.

[116] There was no excitation available due to the field switch being open, hence the generator motored as an induction motor (i.e., asynchronously) at approximately 2,940 to 2,980 rpm. If the field switch had remained closed, the rotor would have operated at the synchronous speed (3,000 rpm).

[117] Callide C and Callide B were also disconnected from the grid when Calvale substation disconnected itself from the grid.

Brady Heywood.

Glossary of Acronyms and Terms

GLOSSARY OF ACRONYMS AND TERMS

A

B

C

D

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Brady Heywood.

Appendix Part A

Technical Investigation Appendices

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Appendix Part B

Organisational Investigation Appendices

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