INVESTIGATION REPORT

From: Investigation Team

Date: 13 October 2017

To: [redacted]

Authors: [redacted]

FIM nr.: 1903957

REFINERY SHUTDOWN AFTER POWER FAILURE IN 25 KV STATION 4

This report describes the results of the investigation into the technical causes that led to the fire in 25 kV station Centrale 4 at the Shell Pernis Refinery on July 29th 2017 and the subsequent shutdown of all refinery and chemical units. It includes the time line and causal tree of the refinery shutdown. Based on the investigation, actions are defined in below mentioned working areas and/or -processes. The report is shared with the relevant Site Process Owners (SPOs), Site Process Focal points (SPFPs) and Department Process Focal points (DPFPs), for information and follow up. All required actions are included in the action table and progress will be managed through the Fountain Incident Management System.

Werkgebied of Werkproces	Site Proces Onwer (SPO)	Site Proces Focalpoint (SPFP)	Department Proces Focalpoints (DPFPs)
Electrical Engineering & Assurance (EEA)	[redacted]	[redacted]	Operation Maintenance Coordinators
Emergency Response (ER)	[redacted]	[redacted]	Production Supervisors

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EXECUTIVE SUMMARY

This investigation was done to create an understanding of the technical causes that led to the fire in Centrale 4 at the Shell Pernis Refinery on July 29th 2017 and the subsequent shutdown of all refinery and chemical units.

Centrale 4 is the newest 25 kV electrical station on site and was brought in service in 2007 as part of the Pergen (Air Liquide) Utilities project, that replaced the former Shell boiler houses. The Centrale 4 25 kV system consists of 4 switchgear sections, that provide redundant electrical supplies to the process units. The switchgear sections are interconnected through [redacted] bus ducts, [redacted].

On the 29th of July at 22:12 h, smoke detectors activated an automatic fire alarm in substation Centrale 4, road 109. The fire department responded by visiting Centrale 4 and found smoke on the first floor in the East switchgear room containing part of the 25 kV switchgear. Sparks and a crackling/ticking noise were noticed at the location of the [redacted] bus duct, behind the perforated coving. The site alarm was raised and the "fire" was reported through a push button notification into the Public Reporting System (Openbaar Meld Systeem) at 22:35 h. A CIN (Centraal Incidenten Nummer) notification was made at 22:45 h.

At 23:19 h, a short circuit happened at the 25 kV [redacted] bus duct. The switchgear section of the 25 kV system at Centrale 4 connected to the fault was separated from the other three switchgear sections and was switched off by its protection, as per design. Two of the remaining switchgear sections went into island operation fed from Shell generator 9 (G9), and Pergen generators 20 and 21 (G20 and G21). Subsequently, Pergen G20 and G21 were disconnected from the Centrale 4 Island after approximately half a second. This action was initiated by an undervoltage protection relay at Pergen, which acted at the same time as the Shell directional overcurrent/undervoltage protection initiating the Centrale 4 island. Considering the time delays in protection relays and switches, the timer settings on Shell and Pergen side were not aligned to avoid the disconnection of G20 and G21 from Centrale 4 in this scenario. Next, the fast load shedding system switched off the power supply to Station [redacted] from the Centrale 4 island and the "frequency load shedding system" switched off the power supply to Station [redacted] from the Centrale 4 island. G9 tripped approximately 12 seconds after the Centrale 4 island was initiated resulting in the de-energization of the Centrale 4 island. A further investigation is required to assess which of the secondary systems has not functioned properly.

During these events, several differential protection relays operated upon the detection of a current unbalance. This led to unnecessary disconnection of the power supply to some stations. Furthermore, two cooling water pumps at WPH5 started simultaneously, 7 times in a period of 2,5 seconds. All start attempts were abandoned.

The short circuit, arc-flash and/or explosion that occurred in the switchgear room, led to a fire of the bus duct. The Officer in Charge immediately raised the incident to a GRIP 1 (Coordinated Regional Incident control Procedure). Several attempts were made to extinguish the burning bus duct with CO_2 bottles, blankets and powder and foam. These attempts were unsuccessful. To extinguish the small-scale fire in Centrale 4 with foam, the last remaining 25 kV switchgear section in operation was de-energized at 2:30 on the 30th of July (after approximately 3 hours), which led to a complete power outage of the KLMN area. On the 30th of July at 04:22 h, the fire was extinguished and GRIP-1 ended at 14:00 h.

An independent root cause analysis of the unexpected and unforeseeable defect within the 'maintenance free' and 'self-extinguishing' bus duct is being carried out by DNV-GL (formerly known as KEMA), including forensic analyses and tests to establish the failure mechanism of the [redacted] bus duct.

The power failure and fire ultimately led to the shutdown of all refinery and chemical units. It was decided to shut down most of the units at the ABC Area mainly in view of foreseeable feedstock shortages. Most of the units in the DE Area were shutdown due to the limited availability or non-availability of cooling water, instrument air and steam. This was partly the result of an indirectly related Pergen (Air Liquide) utility failure at 00:35 h on the 30th of July. At the KLMN Area, most the units tripped at 23:19 h on the 29th of July, other units were taken down in steps due to the loss of cooling water. Around 01:00 h on the 30th of July, all units at the KLMN Area were down.

Including cleaning, recovery and verification that the units were safe to start, it took SNR [redacted] to finalize the restart of all units.

A full analysis has been carried out to verify the cause of each unit trip on the 29th and 30th of July. This analysis revealed the complexity of the electrical network and protective functions.

Based on the investigation findings to date, the following actions will be carried out:

1) Complete the forensic investigation and root cause analysis of the failure of the bus duct system by DNV-GL.
2) Investigate which of the secondary systems of Generator 9 and Gasturbine 3 have not functioned properly.
3) Investigate why the cooling water pumps in WPH5 restarted simultaneously and why the restarts were unsuccessful.
4) Investigate why Station [redacted] was disconnected by the Frequency Load Shedding system.
5) Remove the "current unbalance" settings on the differential protection relays that opened upon the detection of a current unbalance.
6) Strengthen the assurance protocols of electrical protection relay settings during projects and replacements.
7) Carry out a combined Shell-Pergen system study for electricity, to fully align control and protective function settings, considering minimum and maximum generation modes and credible failure scenario's.
8) Study opportunities to extinguish fires inside vital electrical stations without the necessity to enter and/or de-energize the entire station.
9) Organize OIC learning sessions with Electrical Engineering and - Maintenance organizations and the Fire Brigade.
10) Share technical learnings of this incident within the Shell Group, VNPI, VNCI and KEGROB.

INCIDENT DESCRIPTION AND IMPACT

On Saturday the 29th of July 2017 at 23:19 h, a fault in an interconnecting high voltage bus duct between the left-hand side and the right-hand side of the 25 kV switchboard in Centrale 4 at the Pernis Refinery in the Netherlands resulted in a power failure tripping most of the eastern part of the Pernis Refinery (KLMN Area) and several units at the western part (ABC Area) and central part (DE Area). Subsequently, it was required to shutdown most of the Refinery and Chemicals units and it took Pernis [redacted] to fully recover including starting up the units again.

This investigation focused on the cause of failure of the bus duct which was the initiating event and how this led to the shutdown of the whole plant, including the part of the emergency response that influenced this outcome.

An overview of the Pernis electrical main infrastructure can be found in Appendix 4 and an explanation of the bus duct in combination with the 25 kV switchgear in Appendix 5.

What was expected to happen in this situation?	The 25 kV switchgear section Left Front switches off when defect is detected due to short circuit current. The Left Rear and Right Rear switchgear sections transfer and continue operation in Island and the Right Front switchgear section continues operation. Units connected to the Left Front switchgear section shut down and units connected to the other switchgear sections continue operation. The bus duct insulation material does not burn, because it is self-extinguishing.
What did actually happen?	In addition to the Left Front switchgear section also the Left Rear and the Right Rear switchgear sections tripped and units connected to these sections also shut down. Furthermore, the [redacted] bus duct caught fire and kept burning for several hours. To extinguish the fire, the remainder of the 25 kV switchboard was switched off.
What were the negative consequences?	Shutdown of the Pernis Refinery and Chemicals Units, including ABC and DE Areas.

OVERALL TIMELINE

The detailed timeline of the events that took place in Centrale 4 and the subsequent plant shutdown can be found in Appendix 1. The most important events are listed below.

29-7-2017 22:10	First of approximately 50 earth fault events detected at 10 fields in Centrale 4 and Load Center 4 (short earth fault events with durations of 6 ms – 120 ms)
29-7-2017 22:12	Automatic fire alarm Centrale 4 (initiated by smoke detection)
29-7-2017 22:29 - 22:31	Report fire brigade: Visual inspection: smoke on 2nd floor and noise (popping/crackling sound) at the location of the 25 kV [redacted] bus duct, behind the perforated coving
29-7-2017 22:43 - 23:04	First attempt to quench the perforated coving with CO_2 (1 bottle used)
29-7-2017 23:10 - 23:20	Inspection of electrical authority on duty (“A-wacht”) in Centrale 4 together with fire department
29-7-2017 23:19:06:094	L2 Phase to ground fault between L2506 and Is-limiter
29-7-2017 23:19:06:156	2-phase (L2-L3) to ground fault between L2506 and Is-limiter
29-7-2017 23:19	Explosion and/or flash, light flash (orange)
29-7-2017 23:19:06:162	Trip Is-limiter
29-7-2017 23:19:06:555	Trip circuit breaker L2511 (feeder LF&LR opened) → Island mode

29-7-2017 23:19:06:617	G20 & G21 (Pergen generators) disconnected from island by Pergen → Island only fed by Shell G9
29-7-2017 23:19:08:730	Trip on overcurrent Load Center 4 L2505 & L2506 to C4 L2503 & L2502 opened → no feed Load Center 4 to Centrale 4 LF rail
29-7-2017 23:19:18:117	Trip G9 → Failure of island
29-7-2017 23:19	Loss of power to [redacted] (KLMN Area). Trip WPH4 + 5 → loss of cooling water KLMN + DE Area. Trip [redacted] (ABC Area). Cooling water failure for [redacted] units KLMN Area.
29-7-2017 23:35	Trip Pergen generator G5 (due to loss of cooling water)
29-7-2017 23:45	Firemen make exploration round. Second attempt to extinguish the fire (2 bottles of CO_2 used).
30-7-2017 00:34	Loss of steam to KLMN + DE Areas
30-7-2017 00:50	Loss of instrument air to KLMN + DE Area
30-7-2017 2:30	Manually opened 2 feeders Load Center 4 to Centrale 4 RF → Centrale 4 de-energized to safely apply foam/water Loss of power [redacted]
30-7-2017 2:38	Attempt to extinguish fire using foam
30-7-2017 3:06	Attempt to extinguish fire using ABC powder (dry chemical fire extinguisher) + welding blanket
30-7-2017 4:10	Attempt to extinguish by removing insulation + use of water and monnex powder
30-7-2017 4:22	Fire extinguished
30-7-2017 8:00 – 1-8-2017 8:30	Controlled shutdown of Pernis

ELECTRICAL TIME SEQUENCE

On the 29th of July at 22:12 h, smoke detectors activated an automatic fire alarm in substation Centrale 4, road 109. The fire department responded by visiting Centrale 4 and found smoke on the second floor in the East switchgear room containing part of the 25 kV switchgear. Sparks and a crackling/ticking noise were noticed at the location of the 25 kV [redacted] bus duct, behind the perforated coving. The bus duct is a solid connection used to connect the left and right sides of the switchgear in Centrale 4. The East and West switchgear rooms are separated by a soot wall, see the 1st Floor in Figure 1.

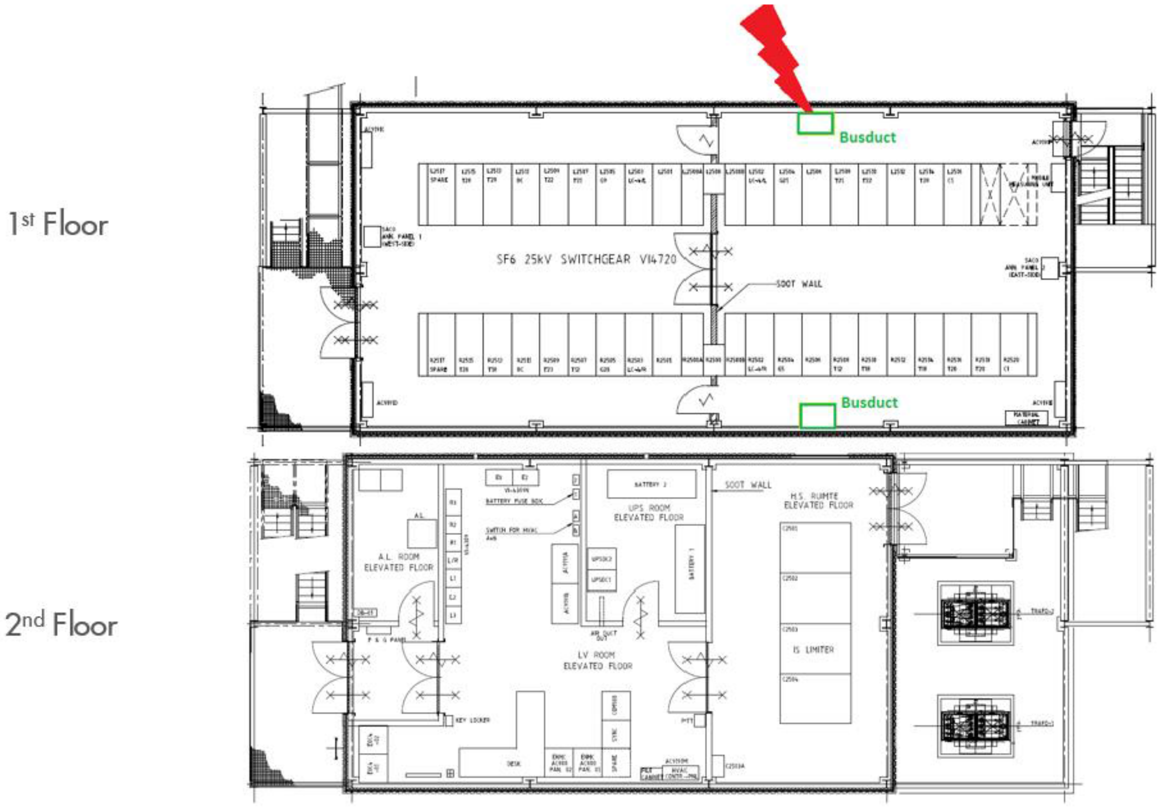


Fig.1: Overview of first (switchgear room) and second (auxiliary and Is-limiter room) floor of C4

The Electrical Authority on duty (A-wacht) was requested to come to the site. Together with the fire brigade he visited Centrale 4. In the switchgear room smoke was visible, together with some soot at the floor close to the [redacted] 25 kV bus duct behind panel L2506 (this is the bus duct system between the Is-limiter and the Left Front switchgear section). Inspections in the other rooms of the building did not show any smoke or other anomalies.

At 23:19 h, a short circuit, arc-flash and/or explosion occurred in the switchgear room, just as the team left the building from the Is-limiter room on the second floor. The team noticed a loud bang and an orange flash coming from the switchgear room.

From the Electrical Network Monitoring and Control (ENMC) system, it has been established that the loud bang was a two-phase earth fault/short circuit (23:19:06:156 h (Hour: Minute: Seconds: Millisecond)) at the [redacted] bus duct behind the 25 kV switchboard feeder L2506.

Figure 2 shows the fault location in the Centrale 4 in a simplified single line diagram.

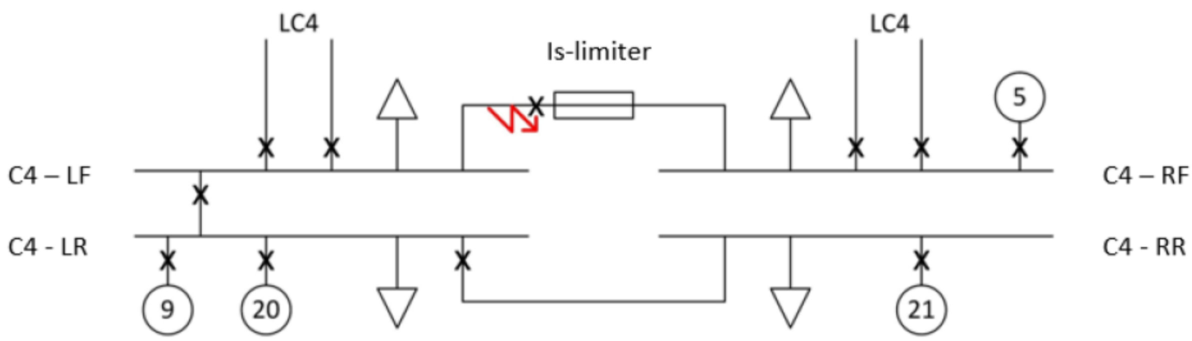


Fig.2: Fault location Centrale 4

Because of the short circuit current the Is-limiter was activated (23:19:06:162 h) followed by the Circuit Breaker in series with the Is-limiter (23:19:06:212 h). The trip of the Is-limiter and corresponding Circuit

Breaker resulted in the separation of the Left Front switchgear section and the Right Front switchgear section. At this stage, all four switchgear sections were still energized and the Left Front switchgear section and Rear bus bar were still connected (see Figure 3).

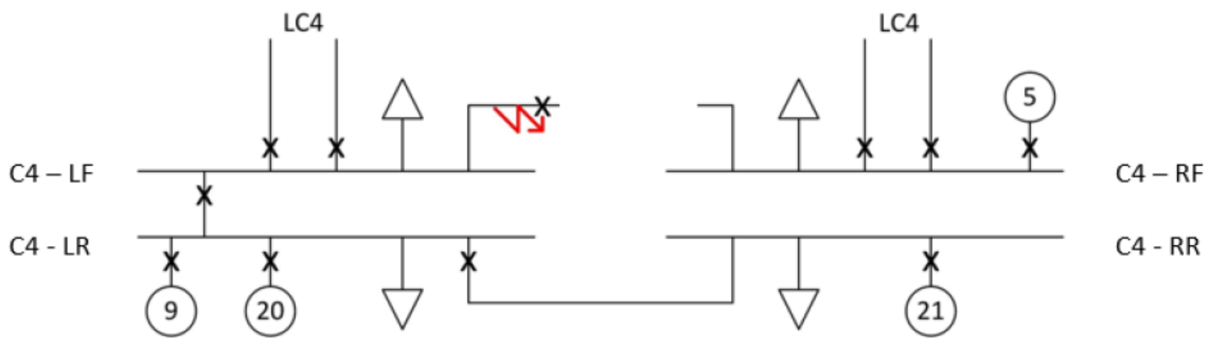


Fig.3: Is-limiter activated segregating Left and Right Front bus bars

Note that an Is-limiter is a fast acting protection device, often used in couplings between 2 (parts of) systems, whose short circuit withstand capability would not be sufficient with parallel connection via a circuit breaker. Due to the significant power generation and in-feeding transformers, in case of a short circuit without an Is-limiter, the current would exceed the short circuit breaking capacity of the switchgear circuit breakers. The Is-limiter segregates the Left-hand side from the Right-hand side as soon as a short circuit is recognized reducing the short circuit current to a level that the circuit breakers can switch off.

Due to the under-voltage in combination with the over-current from the Rear bus bar to the Front bus bar, the bus coupler between the Left Front switchgear section and the Left Rear switchgear section was opened (23:19:06:555 h) by its protection relay. This resulted in the initiation of the Centrale 4 Island (Left Rear and Right Rear switchgear sections). The Island was being supplied from the generators G9, G20 and G21.

Shortly after the initiation of the Centrale 4 Island, the feeders from the Island (Rear) bus bar with Generators G20 and G21 (both from Pergen) were opened (23:19:06:617 h), resulting in the Centrale 4 Island only being fed from Generator G9 (see Figure 4).

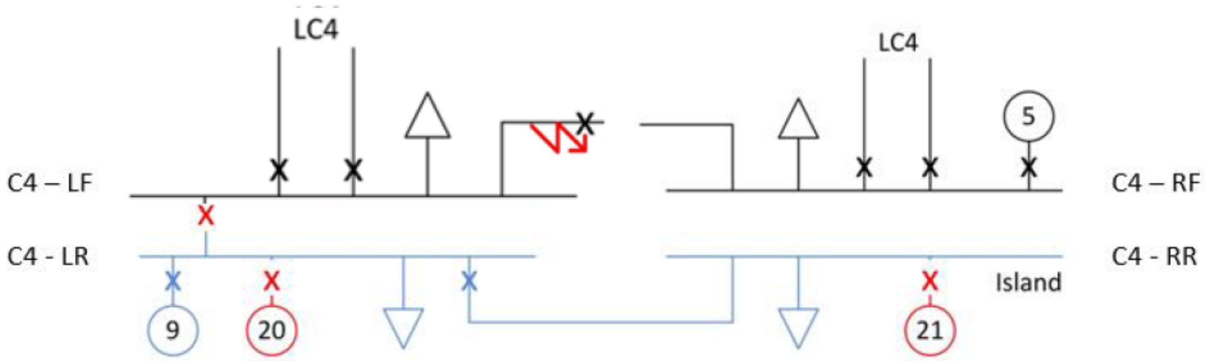


Fig.4: Rear bus bar Centrale 4 in Island and disconnection of G20 and G21

At this stage, the Left Front switchgear was still energized from Load Center 4 (LC4). This switchgear section was disconnected from the last remaining two supplies by trip of the feeders from Load Center 4 on overcurrent (23:19:08:730 h). These two actions isolated the fault location and de-energized the Left Front switchgear section. Units connected to the LF rail included [redacted]. The three other switchgear sections were still energized (see Figure 5).

Two cooling water pumps were running at WPH5 prior to the incident, P1 on [redacted] L604 and P3 on [redacted] R604. Both motor feeders in [redacted] opened at 23:19:06:429 h resulting in a trip of both pumps. During the island operation in approximately 2.5 seconds seven start attempts of both cooling water pumps P1 and P3 at WPH5 were executed at the same time.

Substation [redacted] was disconnected from the island by the Fast Load Shedding system (23:19:07:115 h). Units connected to this substation included [redacted].

Due to a phase unbalance the differential protection tripped the supplies to [redacted] (23:19:07:573 h) and [redacted] (23:19:07:581 h) as well as [redacted] (23:19:08:307 h) resulting in substation TS40 being de-energized (tripping HDS-6) and substation TS29 being fed only via TR2 from the C4 island.

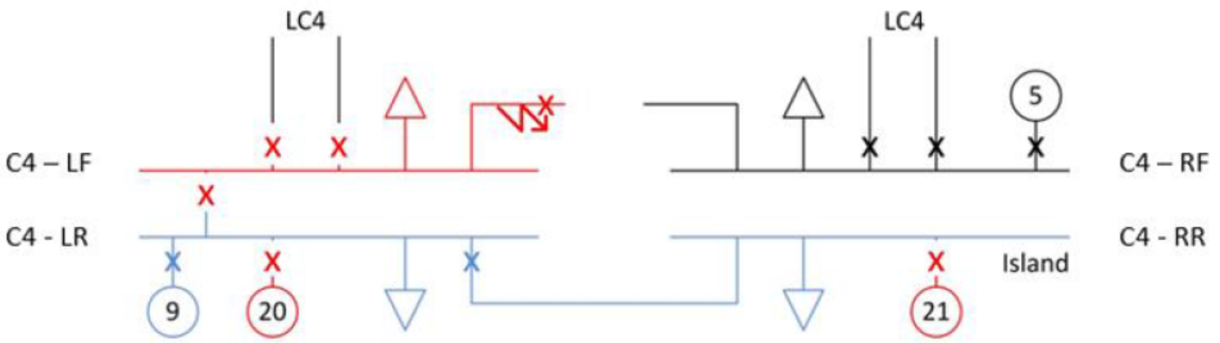


Fig.5: Left Front section disconnected on over-current protection

The frequency based back-up load shedding system shedded [redacted] (23:19:10:115 h) from the island. Units connected to this substation included the [redacted]

Due to a phase unbalance the differential protection tripped the supply to [redacted] (23:19:16:055 h), resulting in [redacted] being de-energized, after [redacted] had already tripped before. This resulted in the trip of WPH4.

Approximately 12 seconds after the island was initiated, Generator G9 tripped (23:19:18:117 h). Because G9 was the last remaining generator feeding the island, the island (switchgear sections Left Rear and Right Rear) were de-energized, see Figure 6.

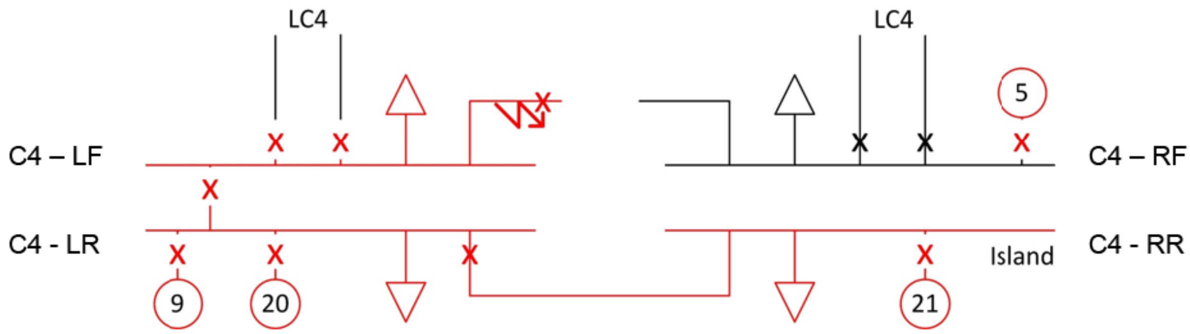


Fig.6: Island de-energized after G9 trip

At this stage, only the switchgear section Right Front was still in operation and was fed by Load Center 4 and G5. G5 tripped after 15 min (at 23:35 h). For the fire department to safely apply foam/water on the location of the fire, the two feeders to this section from Load Center 4 to Centrale 4 were manually opened. This resulted in de-energizing the complete 25 kV switchgear in Centrale 4 (02:30:28:117 h). Between 04:10 and 04:22 the burning material was removed from the bus duct and the fire was safely and successfully extinguished.

TRIP AND SHUTDOWN SEQUENCE OF THE UNITS

In Appendix 3, an overview is given of the shutdown of all units on site. At the ABC Area, most units were taken down in a controlled fashion. Exceptions were the [redacted] which tripped due to process upsets and the [redacted]-[redacted] which tripped due to the power failure. All these units tripped at 23:19 h on the 29th of July. At the DE Area, most Shell units stopped immediately at 23:19 h. The only exception is [redacted] which stopped around 0:50 h on the 30th of July. At the KLMN Area, [redacted] tripped at 23:19 h. At [redacted], the units were taken down in steps, starting 23:19 h due to loss of cooling water. Around 1:00 h, all units were down.

EMERGENCY RESPONSE SEQUENCE

On the 29th of July at 22:12 h, smoke detectors activated an automatic fire alarm in substation Centrale 4, road 109. The Shell Emergency Response Team immediately responded to the alarm, went to the substation and carried out a visual inspection in the building. At 22:35 h, the Incident Commander reported back that smoke was present and crackling sounds were heard at the second (mid) level of the 3-story building. He requested the initiation of the site first alarm. At 22:35 h, the site alarm was raised and the fire was reported through a pushbutton notification into the Public Reporting System (Openbaar Meld Systeem). The electrical authority on duty ('A-wacht') was requested to come to the site.

During further visual inspections, sparks and crackling sounds were noticed at the location of the 25 kV [redacted] bus bars on the east side of the building behind the perforated coving. A first attempt was taken to cool the perforated coving with a CO_2 extinguisher. A CIN notification was raised at 22:45 h.

A first inspection by the electrical person on duty was done between 23:10 h and 23:20 h. At 23:19 h, a short circuit, arc-flash and/or explosion occurred at the second level within the building, which led to a fire in the [redacted] bus bar system. The Officer in Charge raised the incident to a GRIP 1 (Coordinated Regional Incident control Procedure).

Further inspections between 23:20 h and 23:45 h revealed the absence of the perforated coving. A first attempt was done to extinguish the burning bus bar system with CO_2. Two bottles were used unsuccessfully.

The COPI (COmmand Place Incident) arrived at 00:08 h on the 30th of July.

At approximately 02:30 h, Centrale 4 was entirely de-energized, but earthing was not possible. Using foam, the fire brigade attempted to extinguish the fire from a safe distance between 02:38 h and 03:06 h. They were unsuccessful. A third attempt was made between 03:06 h and 03:23 h, with blankets and powder, but was again unsuccessful. Finally, between 04:10 h and 04:22 h, the burning isolation material was removed from the bus bar system and the fire was successfully extinguished with water and monnex powder.

The situation was declared "Brand meester" (Fire under control) at 05:50 h and the GRIP-1 was ended at 14:00 h at which time the COPI was also discontinued.

Fig.7: [redacted] bus bar system during the installation in 2007, during the fire and after the fire

ACTIONS TAKEN DIRECTLY AFTER INCIDENT

After the fire was extinguished, the following 4 work streams were set-up (explained in more detail below):

- Cleaning Centrale 4
- Emergency supplies
- Recovery of power supply
- Investigation of the incident (subject of this report)

At the same time, several other activities and processes were started in parallel to enable the safe start-up of the site. A RFSU (ready for start-up) team was formed which focused on getting all units on the site ready to start-up. As part of this process all units for which the shutdown was uncontrolled received a so-called Statement of Fitness (SoF). This overall SoF consisted of a PSSR (Pre Start-up Safety Review) and three partial SoF's for respectively instrumentation, rotating equipment and static equipment. Furthermore, a PIT (product in tank) team was formed which coordinated the actual start-up. This team worked 24/7 and kept an overview over the site, including providing the site with daily updates about the progress.

CLEANING CENTRALE 4

A specialized company was contracted to recondition the 25 kV switchgear, the protection and control systems, all other equipment in the building (e.g. servers) and the building itself. The building has a cable cellar, two switchgear rooms (East and West) and a second floor with an Auxiliary room and the Is-limiter room. The East switchgear room was the most heavily polluted with soot and extinguishing fluids as the fire was in this part of the building. The West switchgear room was less polluted, mainly with soot. The second floor had light pollution from soot and the cable cellar was polluted with extinguishing fluids, leaking through the ceiling from the switchgear rooms.

As the West switchgear room was least polluted switchgear room, the first focus was on this side, together with the required auxiliary room and cable cellar. The cleaning of this side was a significant job as the fire produced a large amount of smoke and thus soot [redacted]. The soot was not only found on the interior of the building and on the switchgear panels, but also inside the switchgear panels and secondary systems, such as servers and protection relays. The photos in Figures 8 and 9 give an impression of the situation in Centrale 4 after the fire.

Fig.8: Centrale 4 switchgear before and after cleaning

Fig.9: Centrale 4 switchgear East Left from behind, near location of fire

The cleaning of the East side of the building commenced after the West side [redacted].

EMERGENCY SUPPLIES

The normal emergency supplies of Shell Pernis are emergency diesel generators, mainly for all the lighting, and UPS systems for process critical installations such as DCS systems and fire and gas detection. As the UPS systems have a limited autonomy time, during a prolonged outage extra emergency power supplies should be connected to these systems. A separate team from Electrical Engineering, Maintenance and Construction departments engineered these supplies, performed the Management of Change process, arranged the required emergency supplies and constructed and commissioned the supplies. During re-energization of the KLMN Area, a separate team was responsible for disconnecting all emergency supplies and restoring the installation to its original condition.

RECOVERY OF POWER SUPPLY

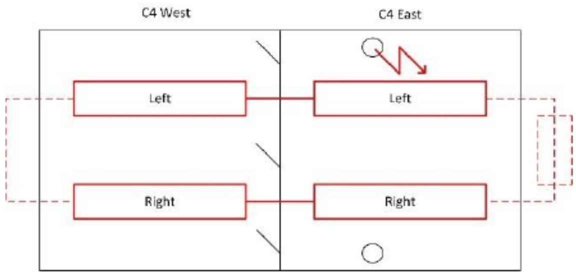
The West switchgear room was less polluted than the East switchgear room. First re-energizing only the switchgear on the West side would mean a quicker recovery of the power on KLMN Area. To do so, a plan with four phases was developed to completely recover Centrale 4 in the quickest way. For all phases of the recovery of the power supply, several scenarios were calculated looking at start-up and running loads of the plants as well as short circuit capacities.

The first phase was disconnecting the switchgear between the two sides, splitting the Centrale in two halves, see Phase 1 in Figure 10. Now all cleaning activities could be focused on the West. After cleaning of the building and the internals of the switchgear and secondary systems, the OEM of the switchgear performed detailed inspections and completely re-commissioned the West side of Centrale 4. On [redacted] the West side of Centrale 4 was re-energized and consequently on [redacted], the complete electrical infrastructure on the KLMN Area (23 high voltage and 33 low voltage switchboards) was re-energized. Although all power could be restored and thus all critical systems could be started up, not enough capacity was available to start all plants on KLMN Area. Furthermore, until the Is-limiter is restored, only one of the four generators on KLMN Area could be running as otherwise the short circuit capacity of the installation would be exceeded during an incident.

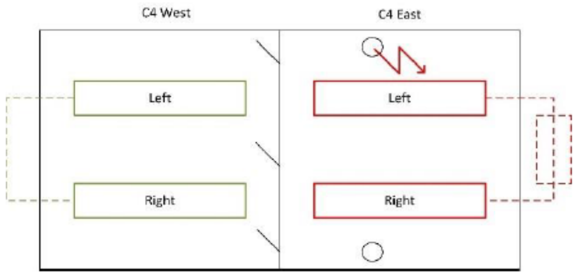
In Phase 2 (see Figure 10) a tent was placed over the Right section of Centrale 4 East to clean, inspect, re-commission and re-energize this section, without having to clean the rest of the East side. Maximum effort was focused on the Right section as it was expected that the Left section was polluted most severely and damage to the switchgear could be expected as the fire was closest to this section. After re-energizing the Right East section, more capacity was available and all process plants could be restarted.

During internal inspection of the Left section of the East side, several damaged parts were found. As there was a delivery time for these parts of [redacted], a Phase 2.1 was required to energize only the bus bar of Left West section and using this to only energize the second, redundant, power supply to Water Pump House 4. After delivery and installation of the parts it was possible to re-connect Left East to Left West in Phase 3 (see Figure 10). [redacted].

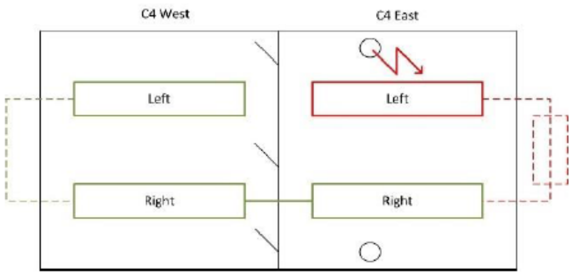
In Phase 4 (see Figure 10) the bus duct to the Is-limiter between the Left and Right section will be rebuild. When this is completed, the Is-limiter can be used again, allowing all generation capacity to be reconnected to Centrale 4 and thus restoring Centrale 4 to its normal configuration.



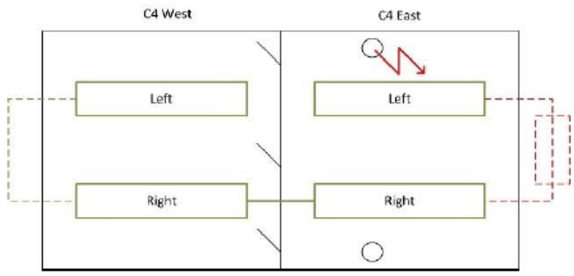
Situation of Centrale 4 after the fire



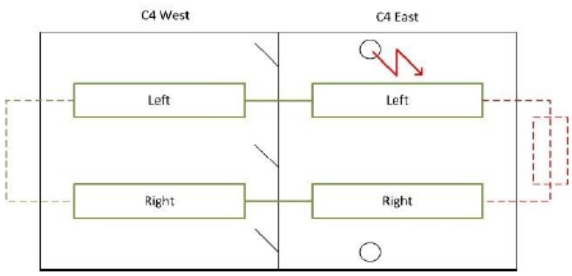
Phase 1: West energized first



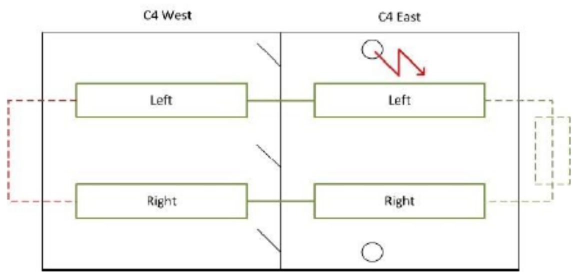
Phase 2: right East energized via West



Phase 2.1: East Left energized via one feeder



Phase 3: East Left coupled with West



Phase 4: fully recovered

Fig.10: All phases of Centrale 4 recovery, red is de-energized, green is energized

INVESTIGATION METHODOLOGY

The Shell investigation team was appointed on the 31st of July and consisted of the following members:
- [redacted] – HSSE External Affairs Manager at Pernis
- [redacted] – Manager, Business Opportunity Management & Capital Planning at Pernis
- [redacted] – Technical Safety Engineer at Pernis
- [redacted] – Principal Electrical Engineer at P&T Rijswijk

In September, [redacted] (Team Lead Electrical Maintenance Engineering & Specialist Engineer Electrical at Pernis) was added as liaison between the electrical organizations of Pernis and P&T Rijswijk.

Timelines and a causal tree were established, supported by data collection and interviews, and sessions with key people to test the work done and to provide input to the recommendations. This resulted in the underlying report.

Furthermore, DNV GL was asked by Shell to carry out an independent forensic investigation into the fault in the interconnecting high voltage bus bar of Centrale 4. DNV GL (formerly KEMA) is very experienced in power failure investigations with over a century of experience. The approach for this investigation is indicated in Figure 11 which is to guarantee a comprehensive consideration of all possible root causes. To enable this investigation the [redacted] bus bar failed side was transported to DNV GL in Arnhem.

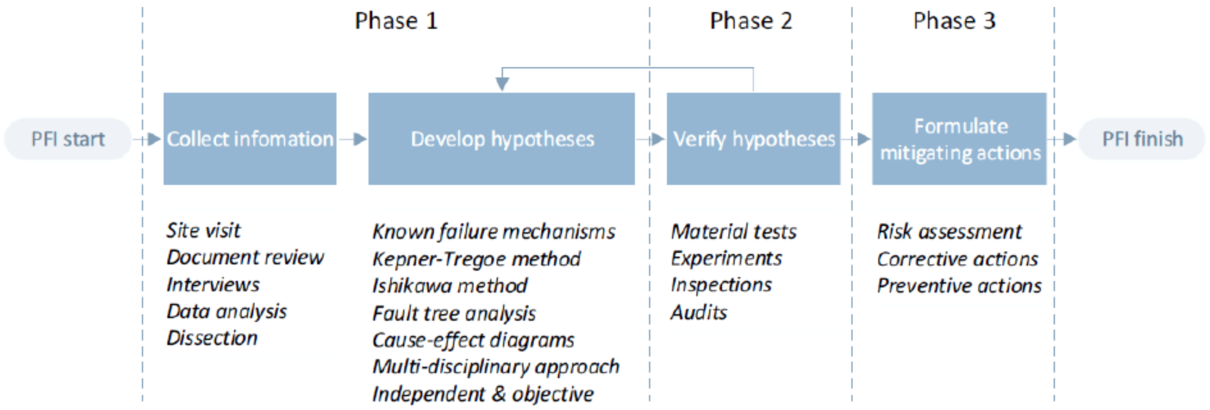


Fig.11: Approach investigation by DNV GL

The following research questions were agreed between Shell and DNV GL:
A. Why did the bus duct fail?
B. How has the response of the protection system affected the observed damage?
C. Why did the failure result in extensive fire damage?

To answer these research question DNV GL is executing the following steps.
1) **Site inspections.** Visual inspections and how the bus ducts have been installed electrically and mechanically, and to document any irregularities or abnormalities e.g. the damage resulting from the failure.
2) **Review of information and documentation.** All available information regarding the failure, the bus duct, its operational history, and the surrounding network is being analysed to determine any irregularities. The review assesses the available information to judge whether the bus ducts have been specified, designed, produced, installed, operated and maintained correctly and per relevant standards. The history of the bus duct system with sparking behaviour and changes to its earthing system is being investigated. The specific circumstances prior to and during the failure is being analysed. Based on the above a timeline of events is created.
3) **Review of protection system actions.** The event list, alarm list and disturbance recordings is being analysed to determine the sequence of events between the first detection of the onset of the fault and finally the successful clearing of the fault from the system. The actions of the protection system are being compared with the intended operation. The scope of the analysis is limited to the protection system actions which have had an impact on the extent of damage directly related to the bus duct failure.

4) **Dissection of the failed bus ducts**. Although the failed bus ducts have been largely destroyed by the resulting fire, the upper connection tubes are damaged but still intact. DNV GL opened these tubes carefully to inspect the inside of the tubes, the sliding contacts, the bus bar insulation, the connecting tube flanges and sealing (See Figure 12 for photos taken during this dissection).

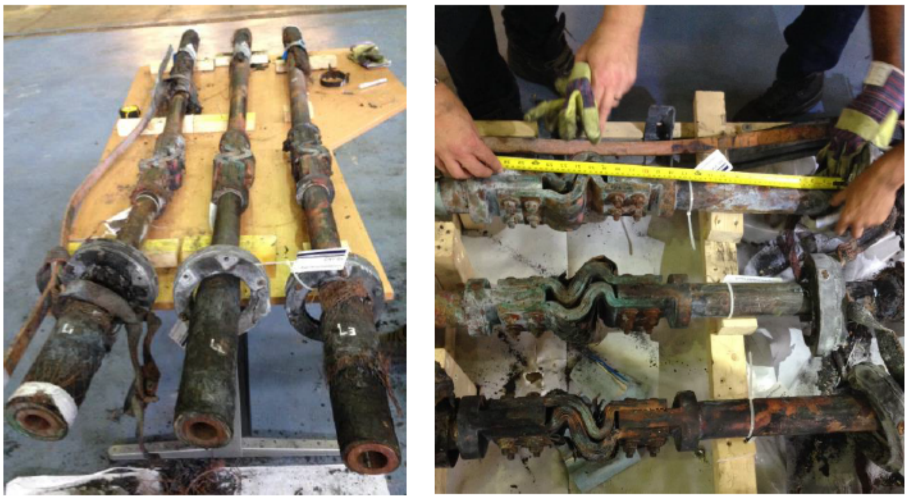


Fig.12: Dissection as part of the Forensic Investigation at DNV GL in Arnhem

5) **Dissection of the non-failed bus ducts.** From one of the undamaged connection tubes a 90-degree cut out in lengthwise direction was made to understand the (electrical) stress control in these connection tubes (see Figure 13). Furthermore, a part of the bus bar, its flexible connection as well as a connection tube have been cut in half in lengthwise direction to understand the (electrical) stress control between the connection tube and the (electrical) stress control at the end of the bus bar (see Figure 14).

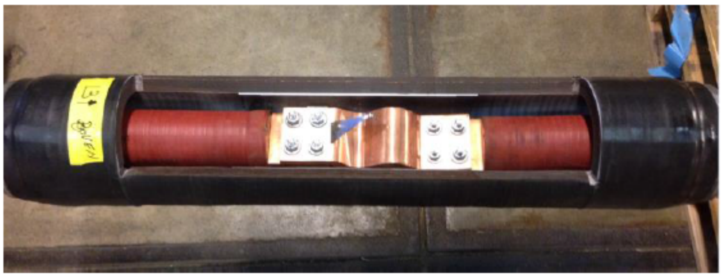


Fig.13: 90-degree cut out of connection tube with flexible connection

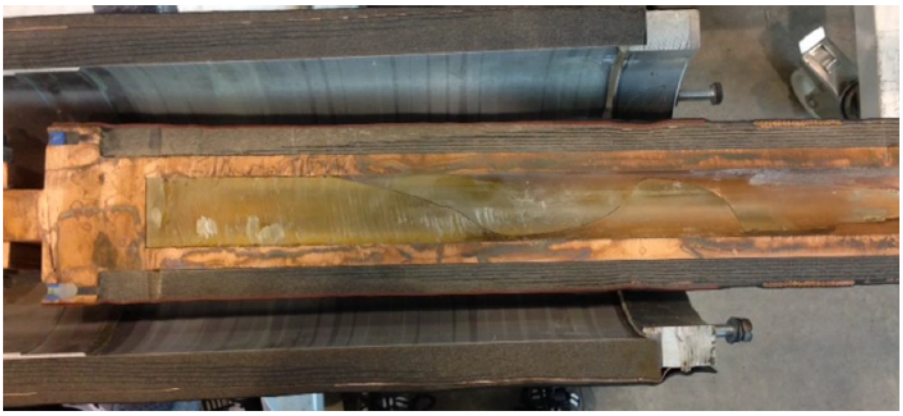


Fig.14: 180-degree cut out of connection tube and bus bar

6) **Partial discharge measurements**. The non-failed side has been transported to DNV GL in Arnhem to be subjected to high voltage tests at the DNV GL High Voltage Laboratory.

   Assess by means of partial discharge measurements using Ultra High Frequency antennas and high frequency current sensors whether the bus ducts exhibit partial discharges (PD) when energized to normal operating voltage. For these PD measurements distinction is made between:
   - PD measurements in Pernis (Centrale 4 and Load Center 4).
   - PD measurements at the High Voltage Laboratory in Arnhem on the undamaged bus ducts. The purpose of this test is twofold:
     a) To test for PD in the laboratory after bus duct installation on one of the phases from the east side of Centrale 4. (NB: To start with PD free individual components all individual components (bus ducts parts and connection tubes) have been tested for PD in the laboratory before the complete phase is assembled).
     b) To study the effect of misalignment and/or improper installation of the insulated bus ducts and insulating connection tube, this will be done by moving the insulated connection tube, in the lengthwise direction of the bus duct.

   A complete reassembly (by [redacted] as original manufacturer of the bus duct) was made of one of the undissected phases, including insulated bus duct, insulated connection tubes and flexible connections at the DNV GL High Voltage Laboratory.
   For the PD measurement, a horizontal test setup of the bus duct was made (see Figure 15) because from an electrical point of view it does not result in any difference in comparison to a vertical setup and from a safety point of view this is much better (no working at heights).

Fig.15: Test setup of at the High Voltage Laboratory of DNV GL at Arnhem.

7) **High Voltage tests.** Establish what, from a (electrical) stress control point of view, the weakest point in a bus duct assembly is by increasing the test voltage well above the maximum design rating which is already well above the nominal operating voltage.
8) **Material tests on bus duct covers**. Assess by means of material tests the thermal history and the suitability (flammability and smoke production) of the bus duct insulation material and the material used
9) **Root cause analysis.** The observations made throughout all the prior inspections, dissections, and information review steps, combined with specialist component and system knowledge will be used to formulate hypotheses regarding the root cause of failure. Depending on the complexity of the case, formal root cause analysis methods such as Kepner-Tregoe may be used for the analysis and the documentation of the root cause.

The Root Cause Analysis at DNV GL is still ongoing the time of writing this report and the process as well as the conclusions will be reported by DNV GL in separate reports.

OUTCOME

The outcome of the present investigation is laid down in the Cause and Effect Diagram which can be found in Appendix 2 and are explained below.

ELECTRICAL

1 Load shedding Centrale 4 in Island mode

When (part of) Centrale 4 is in Island, to keep the 50 Hz grid frequency, the load and generation needs to be balanced. Load shedding systems make sure that there is only an amount of load connected to the system that can be supplied by the running generators. If there is an expected shortage of generation capacity, an amount of load is shed equal to the generation deficiency. Centrale 4 has two load shedding systems, a fast and a frequency load shedding system.

To shed a minimum amount of load and to have a stable Island, two operational conditions are to be met in normal operation:
1. Export from the Island bus bar (Rear) to the grid bus bar (Front) should be between [redacted] MW
2. [redacted] generators should always be running on the Island bus bar (Rear)

1.1 Fast load shedding system

The fast load shedding in the ENMC (Electrical Network Monitoring and Control) system, continuously calculates the balance between load and generation in the system. Every time a critical circuit breaker is opened it will check these calculations if enough generation capacity is available. Critical circuit breakers are circuit breakers that could initiate Island or when in Island could change generation capacity (e.g. bus couplers between Front and Rear (Island) bus bars or generator breakers). The ENMC system then decides whether load needs to be shed according to a pre-determined priority list. For load and generation, a [redacted] second delayed measurement is used to prevent the load shedding system to respond on instabilities in the grid during an incident. For the generators neither the capability nor the measured value is used, but [redacted] MW is added to the measured value and this is seen as the capability of the generator in Island at each moment in time. This allows the generator to ramp up its output power if required.

Before the incident G9 was running at a low output of 10,38 MW (yearly average is [redacted] MW). All the other measurements available in ENMC system just before the incident, indicate a normal situation. See all loads connected to the Island bus bar in Table 1.

Station	Main loads	Load	Generation
[redacted]	[redacted]	2 MW (estimate)	
[redacted]	[redacted]	9,39 MW	
[redacted]	[redacted]	0 MW	
[redacted]	[redacted]	2,58 MW	
[redacted]	[redacted]	1,78 MW	
G9			[redacted] MW
G20			[redacted] (on C4)
G21			[redacted] (on C4)
Sum:		**15,75**	**20,35**

Table 1: Loads and generation on Island bus bar

Before the incident, [redacted] three generators were connected to the Island bus bar (Rear) and 11,24 MW was exported over the bus coupler between Island (Rear) and Front bus bar [redacted]

At 23:19:06:555 h Centrale 4 Island was initiated, quickly followed by disconnecting of G20 and G21 62 ms later at 23:19:06:617 h. Both circuit breakers are critical circuit breakers and at both moments in time the Load Shedding system checked its calculations to decide if load shedding is required.

Using the measurements of the ENMC system, the load shedding calculations at opening of both critical circuit breakers can be reconstructed, see Table 2. Note that the calculated values in the last column are not just the sum of the row, as this calculation uses the [redacted] delayed measurements and adds [redacted] to the G9 output power.

1. When the Island is initiated by disconnecting the Island (Rear) bus bar from the Front bus bar at 23:19:06:555 h, the load shedding system calculated a surplus in generation capacity of 6,64 MW, no load shed is required
2. When Pergen went into Island by disconnecting from the Centrale 4 Island (Rear) bus bar at 23:19:06:617 h, the load shedding system calculated a deficiency in generation capacity of 3,33 MW. This means the first connected priority of at least 3,33 MW will be shed, in this case [redacted] with 9,39 MW.

The conclusion is that the fast load shedding system worked as intended.

Time	Event	Load Island bus bar						Generation G9	Available MW G20 G21	Load Shed calculation
		[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	Sum			
	Before incident	2	9,39	0	2,54	1,78	15,71	[redacted]	[redacted]	6,64
23:19:06:212	Trip IS limiter	2	9,39	0	2,54	1,78	15,71	[redacted]	[redacted]	6,64
23:19:06:429	Trip KWP[redacted]	2	9,39	0	2,54	0	13,93	[redacted]	[redacted]	6,64
23:19:06:515	Trip KWP[redacted]	2	9,39	0	0,93	0	12,32	[redacted]	[redacted]	6,64
23:19:06:555	Island	2	9,39	0	0,93	0	12,32	[redacted]	[redacted]	6,64
23:19:06:617	Island Pergen	2	9,39	0	0,93	0	12,32	[redacted]	0	-3,33
23:19:06:893	Load shed TS20	2	0	0	0,93	0	2,93	[redacted]	0	-3,33

Table 2: Fast Load shedding calculation ENMC system

1.2 Frequency load shedding

Frequency load shedding switches off load depending on system frequency (f) or speed of system frequency drop (df/dt). It reacts to system frequency drop that occurs due to an actual generation shortage in the system. When fast load shedding has operated successfully this situation will not occur. Therefore, frequency load shedding acts as a back-up for fast load shedding.

The frequency load shedding system sheds load according to the same priorities as the fast load shedding system. When a frequency threshold is reached, the substation with the first priority of those connected to the Island (Rear) bus bar is shed. In this way, the system accounts for loads that were not connected to the Island (Rear) bus bar before Island initiation.

See Figure 16 for a schematic overview of the frequency load shedding, coordinated by two RET670 relays.

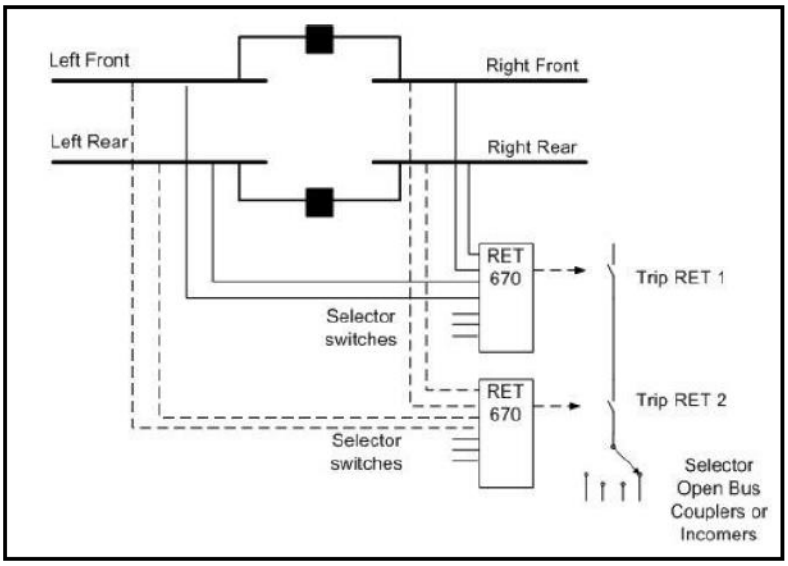


Fig.16: Frequency load shedding

The RET670 relays measure the frequency and provide the ENMC system with an output command for shedding load according to four stages. The ENMC system then looks in its priority table what substations correspond to each stage. Only when both relays have the same output, the ENMC system will shed the corresponding loads. The frequency settings of the frequency load shedding stages are (ref: Functional Design Specification Electrical Network Monitoring & Control System):

1. Stage 1 f = 47,5 Hz with 0 ms delay or df/dt ≥ -4 Hz/s
2. Stage 2 f = 47,0 Hz with 0 ms delay
3. Stage 3 f = 46,5 Hz with 0 ms delay
4. Stage 4 f = 46,0 Hz with 0 ms delay

In Figure 17, the output power of G9 in actual power (MW) and reactive power (MVAr) is plotted as well as the bus bar voltage and frequency of the Left Rear (Island) bus bar where G9 was connected to during the incident. The frequency and voltage of the Left Rear bus bar after Island initiation at 23:19:06:555 h and subsequently disconnection of G20 and G21 at 23:19:06:617 h, was equal to the frequency of G9, as this was the only connected generator to the Island at that time.

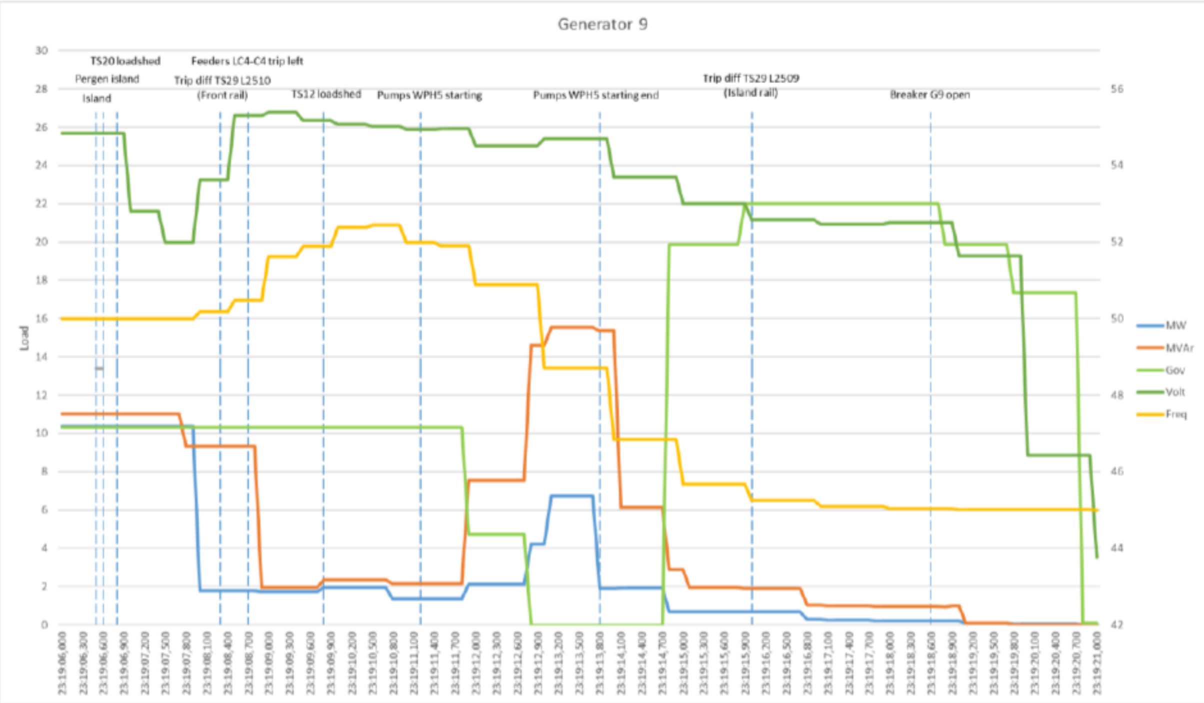


Fig.17: Generator 9 (sampling is based on rate of change in value)

Directly after Island initiation and load shedding of [redacted] by the fast load shedding system, the voltage shortly dips to a minimum of 20 kV, where after quickly restoring to nominal value around 25,5 to 26 kV. In the same period the frequency starts to rise to a maximum of 52,5 Hz. At the moment of load shedding [redacted] at 23:08:19:882 h by frequency load shedding, the frequency of the bus bar is approximately 52 Hz. At this frequency, the load shedding system should never operate as this will only worsen the over-frequency, i.e. increasing load is decreasing frequency and vice-versa.

Substation [redacted] is the last station to be shed with stage 4 priority, i.e. a frequency of f = 46 Hz or lower. In the logs of the RET670 it can be seen that all stages have been activated in a period of 400 ms. See Tables 3a and 3b for relevant events in event list of RET670-1 and RET670-2. Note that these relays do not have proper time stamps as these are not connected to a GPS time server. A 1 in the last column indicates an active signal.

29-7-2017 23:08:19.942	Load Sh.St-4	1
29-7-2017 23:08:19.939	TUF4	1
29-7-2017 23:08:19.899	RCF1 df$2Fdt-	1
29-7-2017 23:08:19.822	Load Sh.St-3	1
29-7-2017 23:08:19.819	TUF3	1
29-7-2017 23:08:19.691	RCF1 df$2Fdt-	0
29-7-2017 23:08:19.636	Load Sh.St-2	1
29-7-2017 23:08:19.635	TUF2	1
29-7-2017 23:08:19.611	RCF1 df$2Fdt-	1
29-7-2017 23:08:19.528	Load Sh.St-1	1

Table 3a: RET670-1 event list

29-7-2017 22:58:12.060	Load Sh.St-4	1
29-7-2017 22:58:12.059	TUF4	1
29-7-2017 22:58:12.019	RCF1 df$2Fdt-	1
29-7-2017 22:58:11.940	Load Sh.St-3	1
29-7-2017 22:58:11.939	TUF3	1
29-7-2017 22:58:11.811	RCF1 df$2Fdt-	0
29-7-2017 22:58:11.757	Load Sh.St-2	1
29-7-2017 22:58:11.755	TUF2	1
29-7-2017 22:58:11.723	RCF1 df$2Fdt-	1
29-7-2017 22:58:11.649	Load Sh.St-1	1

Table 3b: RET670-2 event list

Assuming the ENMC data of the frequency has a fast-enough sampling time to catch all frequency spikes, hence presuming the frequency measurement is correct, the frequency load shedding should not have acted. The reason for this is not well understood and will be investigated further. Additional supporting information is that the event recorder of the generator has not seen an under-frequency at the time of the load shedding of [redacted]

Conclusion is that the frequency load shedding system did not work correctly and that [redacted] should not have been shed. The malfunctioning of the frequency load shedding could be caused by incorrect settings or alternatively that the wrong bus bar measurement is used. The relays and hence the settings are regularly tested. During testing immediately after the incident, the relays worked as intended. Therefore, a setting problem is not likely.
The bus bar measurement used by the RET relays is selected by a manual selector switch in Centrale 4 auxiliary room. This should be selected on one of the two Island (Rear) bus bars as to work in Island mode. As can be seen in Figure 18, the frequency of the Left Front bus bar (bus bar connected to the failed bus duct) falls away at the time of the [redacted] load shedding. As the Left Front bus bar de-energized at 23:19:08:738 h, roughly one second earlier, the voltage and hence the frequency had fallen away from that bus bar section. Although this measurement shows that the frequency only starts to drop exactly at the point where [redacted] is load shedded, it is very likely that this happened earlier. This could be a time synchronization issue. As there is no time delay on the under-frequency settings of the load shedding system, a very short under-frequency will already shed the loads. It is likely that the bus bar measurement was manually selected on the Front bus bar or that there is a cross wiring between the measurement on the bus bars and the selector switch. This will be topic for further investigation.

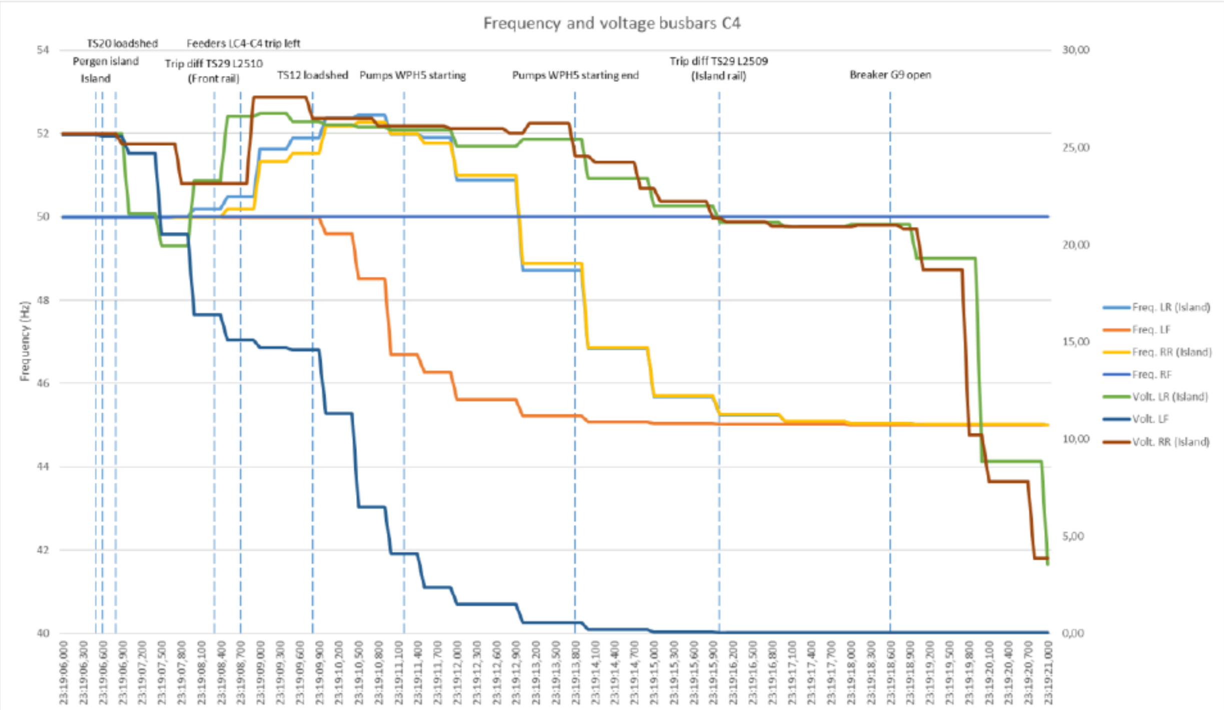


Fig.18: Bus bar frequency and voltages of all C4 bus bars

2 Failure of [redacted]

[redacted]-6 is the only process unit on the ABC Area connected to Load Center 4. At 23:19:07:573 h a differential protection trip signal from LC4 L2509 to [redacted] [redacted] tripped the feeder. At almost the same time (23:19:07:581 h) also a differential protection trip signal from the second feeder from LC4 L2510 to [redacted] [redacted] was activated, tripping also the second feeder to [redacted]

A differential relay measures the current on the beginning and on the end of a cable. When there is a current difference between these measurements this will mean that there is a short circuit or earth fault in the cable, hence the protection trips the cable on both sides. Investigations showed that in this case the differential relays did not trip on the differential function but on an unbalance function. Phase unbalance means that not all phases transport the same current. As one or more phases are disturbed in a short circuit or earth fault situation, as happened during this incident, a phase unbalance is inherent to such a situation. Therefore, an unbalance protection is not used in the standard Shell protection philosophy and especially not in a differential relay as the only function should be differential protection.

These relays were installed [redacted] in 2011-2012. It could not be established how this function was set in this relay during the project. It could either be a setting mistake by the commissioning engineer or a mistake in the firmware by the manufacturer. During regular testing of the relays by the maintenance department this would have not been found as the relay is only tested on its differential function. The firmware will be modified to prevent this trip in the future.

3 Water pump house failures

Water Pump Houses (WPH) 4 and 5 both failed during the incident. WPH4 is supplied by [redacted] and WPH5 by [redacted]

3.1 Failure of [redacted] WPH5

Two cooling water pumps were running at WPH5 prior to the incident, P1 on [redacted] L604 and P3 on [redacted] R604. Both motor feeders in [redacted] opened at 23:19:06:429 h on under-voltage resulting from the phase-to-phase fault in the bus duct. Between 23:19:11:243 h and 23:19:13:889 h pump P1 on L604 tried to restart seven times. In the same period between 23:19:11:797 h and 23:19:13:891 h pump P3 on R604 tried to restart seven times as well. All fourteen restart attempts in these 2,5 seconds were unsuccessful. All motors are protected against too many start attempts as to protect the motor from excessive temperatures in the stator. The starting current is approximately 6 times higher than nominal current, the current heats up the stator and therefore only a limited amounts of start attempts are allowed before the protection stops the attempts to cool the motor down. This protection also prevented these motors from doing more restart attempts.

Detailed modelling of the system is required to find out why the cooling water pumps failed to restart.

3.2 Failure of [redacted] WPH4

Prior to the incident two cooling water pumps were running on WPH4 [redacted] Right (connected to Centrale 4 Island (Rear) bus bar), P9 and P2. At 23:19:06:515 h the motor feeder of P9 opens in [redacted] on under-voltage. No restart attempts have been undertaken.

At 23:19:08:164 h, the differential protection tripped the feeder from L2510 on Centrale 4 Front Left bus bar to L603 in [redacted] This is a three-section board with two feeders and an Automatic Change Over system on the bus couplers. An ACO system closes the bus coupler when one of the sections de-energized, to energize this section from the remaining feeder. At 23:19:09:552 h, the ACO closed the coupler C604 to feed the left side of TS29 with the right feeder.

More than 6s later (23:19:15:986 h), the second feeder (L2509) tripped as well on the Centrale 4 Island (Rear) bus bar due to a differential protection trip, opening R605 on [redacted] at 23:19:16:260 h. The differential relays tripped on unbalance function similar to the [redacted] trip.

4 Island initiation

Island initiation is done by opening the bus coupler between the Front and Rear bus bar, hereby splitting Centrale 4. The Front bus bar stays connected with the Shell Pernis grid, the Rear bus bar is then in Island.

This initiation should be done very quickly after an incident is detected to increase the probability for a successful Island. The initiation should however not be faster than the time the regular protection requires to clear most electrical faults from the system.

This Island is controlled by the Electrical Network Monitoring and Control (ENMC) system. The protection relay of the bus coupler is responsible for the detection if the bus coupler should be opened. The initiation criteria are: ((UV1 *OR* UV2) *AND* (DOC *OR* TOC)) *OR* UF, where:

- UV1 = under-voltage 1st stage U≤[redacted] Un for t>[redacted]
- UV2 = under-voltage 2nd stage U≤[redacted] Un for t>[redacted]
- DOC = bus coupler directional overcurrent I>[redacted] for t>[redacted] Direction from Island bus to LC4 bus.
- TOC = Bus coupler overcurrent I>[redacted] A for t>[redacted]
- UF = under-frequency f≤48 Hz

The trigger for opening bus coupler L2511 during this incident, was an under-voltage of less than [redacted] for longer than [redacted] in combination with a directional over-current from the Rear bus bar to the Front bus bar (i.e. UV2 AND DOC).

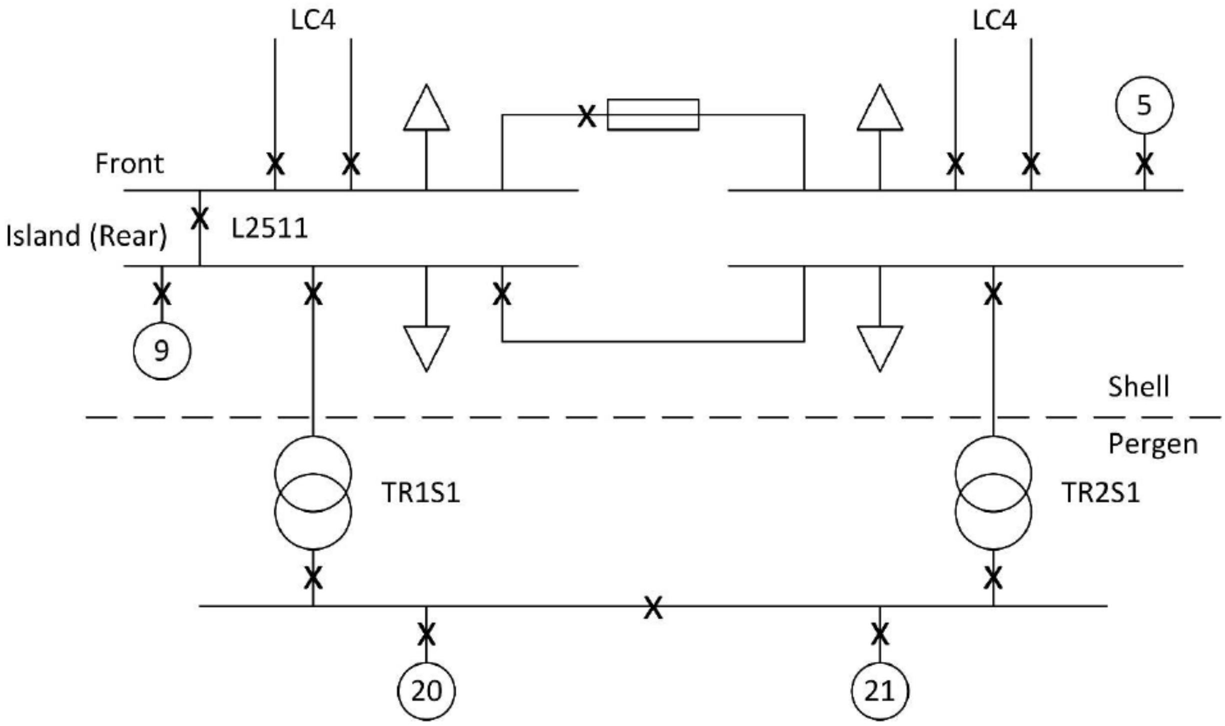


Fig.19: Centrale 4 and Pergen

Pergen can operate their complete installation as an Island as well, separately from Shell Centrale 4. At 23:19:08:612 h, only 62 ms after Shell Island initiation, Pergen disconnected from Centrale 4 by opening the circuit breakers of transformers TR1S1 and TR2S1, see Figure 19. Now the Island (Rear) bus bar was in Shell Island with only G9 and the Pergen installation was in Pergen Island with G20 and G21.

The expectation of Shell was that Pergen would not disconnect whilst in Centrale 4 Island. Only when the Shell Island fails, Pergen was expected to disconnect and go to its own Island. This did not happen as approximately at the same time both Islands are created. Investigation of the Shell and Pergen settings showed that the Island initiation setting of Pergen is on under-voltage and is set at U≤[redacted] Un for t>[redacted] This means that in an under-voltage situation, both Islands are initiated simultaneously. With these settings on Shell and Pergen side one Island is not possible as Pergen settings are actually more sensitive than Shell Island initiation settings. If, according to Shell Island philosophy, Pergen should remain in the Shell Island, then these settings need to be re-calculated and coordinated between Shell and Pergen.

The bus coupler L2511 opened [redacted] ms after the start of the incident, i.e. the opening of the IS-limiter at 23:19:08:162 h. The time required for opening the bus coupler, [redacted] ms, was longer than expected. This is due to processing time in the protection relays. It is recommended to further optimize these processing times to go to Island quicker and hence to increase the probability for successful Island. Although this time could be optimized, the initiation of Pergen Island would not be prevented as the initiation of both Islands happened at the same time.

5 Failure of Island

Because of the disconnection of Pergen generators G20 and G21 only 62 ms after Island initiation at 23:19:08:555 h, G9 was the only generator left in the Island. After load shedding [redacted] and [redacted] and tripping all feeders to WPH4 and WPH5, from 23:19:15:986 h onwards the only load left in the Island was [redacted] (400V auxiliary supply to Centrale 4). As [redacted] has almost no load, the output of G9 lowered to less than 0,5 MW. Finally, almost 3 seconds later at 23:19:18:617 h, G9 tripped and the Island failed.

5.1 Turbine and generator control

The output of a turbine is controlled by a governor and the voltage output of a generator is controlled by an Automatic Voltage Regulator (AVR).

Turbines that operate in the Centrale 4 island are controlled in 'auto' mode. The droop line in the governor is adjusted by the control system (Pergen or ENMC) to maintain the system frequency (primary function) and to achieve equal power sharing (secondary function) between the different units. In droop the governor setting is adjusted depending on the system frequency according to a linear relation (droop line).

Generators use an AVR to adjust the excitation of the generator to control the output voltage of the generator. The ENMC controls the AVR in Island mode also by adjusting a droop line.

5.2 Failure of G9

Two event recorders are available on GT3/G9, one for the generator events and one for the turbine events. The event recorder of the turbine was not active at the moment of the incident.

The relevant events from the G9 event recorder are given in Table 4. The sampling time is 1 second. The events in the list are normalized at the moment of tripping of G9 with the ENMC system. The time stamp is not GPS synchronized. In the last column, a reference is made to the ENMC times. As the values in ENMC are sampled with a certain time, not all frequencies have a corresponding time stamp, i.e. the times are estimated.

Tag	Time in G9 event recorder	Time in ENMC trend
Over frequency 51 Hz	-11 sec	Approx. -9,6 sec
Over frequency 51 Hz	-8 sec	Approx. -6,6 sec
Under frequency 48,9 Hz	-7 sec	Approx. -5,6 sec
Under frequency 48,4 Hz	-7 sec	Approx. -4,6 sec
Under frequency 47,9 Hz	-6 sec	Approx. -4,6 sec
Trip generator breaker	0	23:19:18:617 h

Table 4: comparison G9 event recorder and ENMC events

In table 4 it can be seen that the event times in the G9 event recorder are relatively similar with the event times in the ENMC system.

The generator tripped after opening the generator breaker by the signal ‘Trip generator breaker’. This signal also has a trip function number, 01.05A.B0, which refers to the P<1 MW function of the generator. This is not a protection function but an operational function that sends a trip signal to the circuit breaker when the output power of the generator is below 1 MW and the governor subsequently sends a lowering pulse. It is normally used by operation to take the generator out of service, without having to call in E/I maintenance crew to open the circuit breaker. In the seconds before the trip the generator ran below 1 MW and at the moment of tripping the governor lowered its set point from 22 to 20 MW, activating the P<1 MW function. Subsequently the generator tripped and the Centrale 4 Island fails.
From both event lists, it can be seen that prior to the generator trip, the generator had a serious and prolonged under-frequency of at least 5,6 seconds. The governor set point of the generator is controlled by the ENMC system when in island mode. During the under frequency the ENMC tried to accelerate the driver

by increasing the set point to the governor to a maximum of [redacted] MW, i.e. the generator maximum output. This can be seen in Figure 17. After G9 tripped, the governor lowered it set point again. When initially over-frequency was seen, the ENMC responded (though delayed) by lowering the governor set point as far as 0 MW.

The AVR set points are not trended, only the resulting bus bar voltage, see Figure 17. The voltage in the first 8 seconds was relatively stable around 25 kV. As the frequency started to drop the voltage started to deviate more from the nominal voltage of 25 kV, especially just before the generator tripped when the voltage was as low as 21 kV. It is not yet understood why the AVR was not capable of maintaining a stable voltage.
Neither the instability in the frequency nor the voltage can be explained by events in the Island. After the WPH5 pumps stopped trying to restart at 23:19:13:889 h, the only event in the following 4,8 seconds was the trip of the second feeder of TS29 on differential. However, no parameters indicate a resulting significant step change in load, frequency or voltage. Apart from [redacted] only feeding the low voltage of Centrale 4, no other loads were present in the island after the trip of the second feeder of [redacted] Even then the governor and AVR, both controlled by the ENMC system, could not stabilize the Island.

The frequency instability cannot have tripped G9 as the generator has no under- or over-frequency settings, see Table 5 for the settings. For over- and under-frequency events, only alarms are used. These events have been seen in the event list of G9 during the incident, see Table 4.

U<<	tU<<	U<	tU<	U>>	tU>>	U>	tU>	f<	tf<	f>	tf>
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 5: protection setting G9

The voltage drop cannot have tripped G9 either as the under-voltage setting is at least [redacted] of nominal voltage, so at 25 kV level [redacted] kV. The voltage at the moment of tripping G9 was approx. 21 kV. Moreover, no under-voltage events are recorded in the G9 event recorder. All other protective functions cannot have tripped G9 either as the settings have not been reached and the G9 event recorder shows no events.

Further investigation is required to establish the root cause for the inability of the turbine governor to sustain a stable 50 Hz output and why the AVR was not able to keep a stable 25 kV.

TRIP AND SHUTDOWN OF UNITS

Below an overview is given wat happened to all the Shell units per Area on the site, during the fire and consequential power failure in Centrale 4. Appendix 3 contains a detailed overview about what happened with each unit including the corresponding timeline.

ABC Area

On the ABC Area, most of the units were stopped by a controlled shutdown as decided by the Site Leadership Team. This decision was made because there was no feed available [redacted] and the levels of feed/rundown tanks [redacted] were not visible due to the loss of power on the [redacted].

There are 4 units on the ABC Area which tripped immediately at the power failure at 23:19 h. [redacted].

DE Area

At the DE Area, WPH5 tripped at 23:19 h due to loss of power, as explained in Section 3.1 above. As a result, the units on the DE Area lost their cooling water. This resulted in [redacted]

At about 0:34 h on the 30th of July, steam was lost to the DE Area mainly impacting the DE flare. At 0:50 h, instrument air was lost to the DE Area. The last Shell production unit at the DE Area which was still running was automatically put on hold. At CWZ (water treatment) initially some pumps tripped at 23:19 h due the upset in the electrical system, but these pumps could be restarted quickly and the water treatment kept on running.

KLMN Area

At the KLMN Area the impact of the incident was the largest. The units connected to the LF rail in C4 lost power almost immediately as this was the rail connected to the fault. These units were [redacted]

Substations [redacted] were connected to the island rails RR and LR. As explained above, the connected units tripped when the Island failed. These units were [redacted].

All events described above happened for the KLMN Area in matter of seconds, resulting in a loss of power for 3 out of 4 rails in C4. One rail remained energized, namely rail RF. Substation [redacted] was connected to this rail which supplied power to [redacted]. However, as WPH4 was de-energized when the island failed, the [redacted] units were already almost all taken down by operations, because of the loss of cooling water. This was done mainly by activating the emergency stop buttons. At 2:30 h on the 30th of July, the last rail in C4 was de-energized and therefore power supply to KLMN Area was stopped.

CONCLUSIONS

ELECTRICAL

Based on information from the manufacturer ([redacted] and the installation company ([redacted] the failure and fire of the bus duct system was not expected, nor foreseeable. The system has been designed, manufactured and installed 'maintenance free' and for a 'very long lifetime'. After installation, it was considered forgettable ('fit and forget'). In case of a fire, the Epoxy Resin Impregnated Paper isolation material was considered 'self-extinguishing'. In practice the bus duct system failed, caught fire and the fire lasted 5 hours, after which it was finally extinguished.

The approach for the forensic investigation at DNV GL (former KEMA) is to ensure a comprehensive consideration of all possible root causes. The conclusions of the DNV GL Root Cause Analysis will be recorded in separate reports issued by DNV GL. Some of the failure mechanisms investigated are:

1) Design shortcomings in general or related to the specific application,
2) Manufacturing quality aspects,
3) Installation quality aspects or sub-optimal installation,
4) Partial Discharges due to deterioration,
5) Damage during manufacturing, transport, construction, installation, operation or maintenance,
6) Thermal effects due to high currents, lack of ventilation due to additional plastic covers,
7) Transient high voltages due to earth faults or switching activities,
8) Improper (electrical) stress control due to settlement of the connection tubes and sliding contacts,
9) Earthing arrangements,
10) Ageing of the components,
11) Combination of the above,
12) Any other failure mechanism.

Although the root cause analysis of the bus duct failure has not been finalized, a hypothesis is that the impact of the failure might have been minimized with the application of a dedicated protection.

As a standard, in the Shell worldwide design, switchgear bus bar protection is not applied. It is considered that bus bar faults, especially for bus bars in SF6, are so remote that any protection (bus bar differential) would be contra productive. Such a protection would result in spurious trips when not all Current Transformers (CT) of incoming/outgoing and couplers match for 100%, with a plant shut down due to the trip of these bus bars as the result. Instead, special attention is given to the simplification and integrity of the switchgear bus bar systems in design, manufacturing and installation and corresponding Ingress Protection (IP) making the bus bars a "fault Free Zone".

Bus bar systems connecting switchgear sides are considered as extensions of these switchgear bus bars and dedicated protections are therefore not applied. In case of a fault incoming feeder protection is relied on, which is set as a backup protection for all outgoing feeders.

The fault in the [redacted] bus bar system at Centrale 4 happened at a crucial location in the Pernis electrical power distribution system and had a significant impact. Considering this impact, a review of the standard Shell design is advised and is being considered by Shell Projects & Technology.

As laid down in this report, some unexpected responses of various electrical protection and control systems have been encountered, that did not significantly change the overall outcome of the incident. These are subject to further investigation and optimizations (see Section 'SMART Actions').

TRIP AND SHUTDOWN OF UNITS

The full analysis of all unit trips revealed that all trips could be explained by the power failure and the related protective functions and/or the subsequent utilities failure. Most protective functions have functioned as designed, a limited number of deviations were found but none led to unsafe situations. Most units at the ABC Area were shutdown intentionally, mainly in view of foreseeable feedstock shortages. In all cases the units were successfully brought down to safe conditions.

EMERGENCY RESPONSE

The Emergency Response teams quickly responded to the first automatic fire alarm. Field inspections revealed smoke and the required notifications were made. Duty staff were called in for support and reported timely to site.

Efforts to extinguish the ‘self-extinguishing’ bus duct system initially failed. These efforts ultimately required the substation to be fully de-energized, in line with general fire-fighting training and standard safety procedures for fires in high voltage buildings. De-energizing a substation will always jeopardize all electrical back-up systems and islanding opportunities within the substation. Based on this, it is advised to study opportunities to extinguish fires inside vital electrical stations without the necessity to enter and/or de-energize the entire station.

LEARNING FROM INCIDENTS

SNR wants to learn from incidents, to prevent reoccurrence and to minimize adverse impact on the safety and health of the community and personnel and on the environment. To facilitate learning from incidents, Observation-Insight-Conclusion (OIC) sessions are normally held with the most relevant stakeholders, when the Timeline and Cause & Effect Diagram (CED) have been finalized. The Timeline and CED for the refinery shutdown after the power failure in 25 kV station 4 can be found in Appendices 1 and 2. The most important internal stakeholders are the electrical engineers, electrical maintenance staff and the fire brigade. OIC learning sessions will be held with these groups.

Learnings often exceed the boundary of the own assets and organization. We therefore aim to share important incident findings and learnings within the larger Shell Group and through VNPI, VNCI and Deltalinqs with the relevant Dutch industries. With this internal report, SNR looks beyond responsibilities and/or guilt. The report is not intended to point out legal entities or - persons as responsible or guilty, nor to point out accountabilities. To protect the commercial interests of all parties involved, this report cannot be shared publicly. A learning document and/or presentation will therefore be prepared. It is our intention to share our learnings with VNPI, VNCI, Deltalinqs and KEGROB (Kontactgroep Electrotechniek Grote Bedrijven).

SMART ACTIONS

No.	Action	Risk H-M-L	Owner	Due date
1	Complete the forensic investigation and root cause analysis of the failure of the bus duct system by DNV-GL.	H	Engineering Manager	31/3/2018
2	Investigate which of the secondary systems of Generator 9 and Gasturbine 3 have not functioned properly.	M	Electrical Manager	31/3/2018
3	Investigate why the cooling water pumps in WPH5 restarted simultaneously and why the restarts were unsuccessful.	M	Electrical Manager	31/3/2018
4	Investigate why Station 12 was disconnected by the Frequency Load Shedding system.	M	Electrical Manager	31/3/2018
5	Remove the “current unbalance” settings on the differential protection relays that opened upon the detection of a current unbalance.	M	Electrical Manager	31/12/2017
6	Strengthen the assurance protocols of electrical protection relay settings during projects and replacements.	H	Engineering Manager	30/06/2018
7	Carry out a combined Shell-Pergen system study for electricity, to fully align control and protective function settings, considering minimum and maximum generation modes and credible failure scenario’s.	H	Engineering Manager	31/12/2018
8	Study opportunities to extinguish fires inside vital electrical stations without the necessity to enter and/or de-energize the entire station.	H	HSSE Manager	30/06/2018
9	Organize OIC learning sessions with Electrical Engineering and - Maintenance organizations and the Fire Brigade.	M	HSSE External Affairs Manager	31/3/2018
10	Share technical learnings of this incident within the Shell Group, VNPI, VNCI and KEGROB.	M	Electrical Manager	31/3/2018

APPENDIX 1. TIMELINE

The overall timeline is split in 3 sub timelines: electrical, units and emergency response. The 3 tables below show these timelines and a graphical representation of the three timelines are included.

ELECTRICAL

Table 6 contains the electrical timeline. Note that timelines in electrical systems are very short and therefore times are indicated in milliseconds.

Date + time	Description of event
29-7-2017 22:10	First of approximately 50 earth fault events detected at 10 fields in Centrale 4 and load Center 4. (short earth fault events with durations of 6 ms – 120 ms)
29-7-2017 23:19:06:094	L2 Phase to ground fault between L2506 and Is-limiter
29-7-2017 23:19:06:156	2-phase (L2-L3) to ground fault between L2506 and Is-limiter
29-7-2017 23:19:06:162	Trip Is-limiter
29-7-2017 23:19:06:212	Trip Is-limiter circuit breaker
29-7-2017 23:19:06:429	Both motor feeders [redacted] (L604/R604) opened on under-voltage →trip P1 and P3 at WPH5
29-7-2017 23:19:06:555	Trip circuit breaker L2511 (coupling LF&LR opened) → Island mode
29-7-2017 23:19:06:617	G20 & G21 (Pergen Generators) disconnected from island by Pergen → Island only fed by G9 (Shell Generator)
29-7-2017 23:19:07:115	Substation [redacted] disconnected from island rail RR by fast acting load shedding system. Units connected to this substation include [redacted]
29-7-2017 23:19:07:573	Trip differential protection relay [redacted] (feeder LC4 to substation 40 [redacted]
29-7-2017 23:19:07:581	Trip differential protection relay [redacted] (feeder LC4 to substation 40 [redacted] → [redacted] de-energized
29-7-2017 23:19:08:307	Trip differential protection relay TS29TR1 (feeder C4 LF to substation [redacted] (WPH4)) --> substation [redacted] only fed from island via [redacted]
29-7-2017 23:19:08:730	Trip on overcurrent LC4 L2505 & L2506 to C4 L2503 & L2502 opened → no feed LC4 to C4 LF
29-7-2017 23:19:10:115	Substation [redacted] disconnected from island rail RR by back-up load shedding system. Units connected to this substation include [redacted]
29-7-2017 23:19:11:243	7 x start attempt of both brackish cooling water pumps EP1 & EP3 (WPH5) in 2.5 seconds
29-7-2017 23:19:16:055	Trip differential protection relay [redacted] (feeder C4 LR to substation [redacted] → substation [redacted] (WPH4) de-energized
29-7-2017 23:19:18:117	Trip G9 → Failure of island
29-7-2017 23:35:11:122	Trip Pergen generator G5 (due to loss of cooling water)
30-7-2017 02:30:11:284	Manually opened first feeder LC4 to C4 RF (R2205)
30-7-2017 02:30:28:117	Manually opened second feeder LC4 to C4 RF (R2206) →C4 de-energized

Table 6: Detailed electrical timeline

UNITS

Table 7 shows a coarse timeline for units. In this timeline. A detailed timeline of all the units, including the controlled shutdown on site, can be found in Appendix 3.

Date + time	Description of event
29-7-2017 23:19	Loss of power [redacted]
29-7-2017 23:19	Trip WPH4 → loss of cooling water KLMN Area
29-7-2017 23:19	Loss of power [redacted]
29-7-2017 23:19	Trip WPH5 → loss of cooling water DE Area
29-7-2017 23:19	Trip [redacted] (ABC Area)
29-7-2017 23:20	[redacted] to flare (manual action) --> stop [redacted]
29-7-2017 23:21	Emergency stop button activated for [redacted] manual action)
29-7-2017 23:25	Feed to [redacted]/[redacted] stopped
29-7-2017 23:30	Emergency stop button activated for [redacted], manual action)
29-7-2017 23:38	Emergency stop button activated for [redacted], manual action)

30-7-2017 00:00	Manual stop [redacted]
30-7-2017 00:34	Loss of steam to KLMN Area
30-7-2017 00:34	Loss of steam to DE Area
30-7-2017 00:50	Loss of instrument air to KLMN Area
30-7-2017 00:50	Loss of instrument air to DE Area
30-7-2017 01:00	Manual stop [redacted]
30-7-2017 02:30	Loss of power [redacted]
30-7-2017 02:30	Loss of power [redacted]
30-7-2017 02:30	Loss of power [redacted]
30-7-2017 02:30	Loss of power to [redacted]

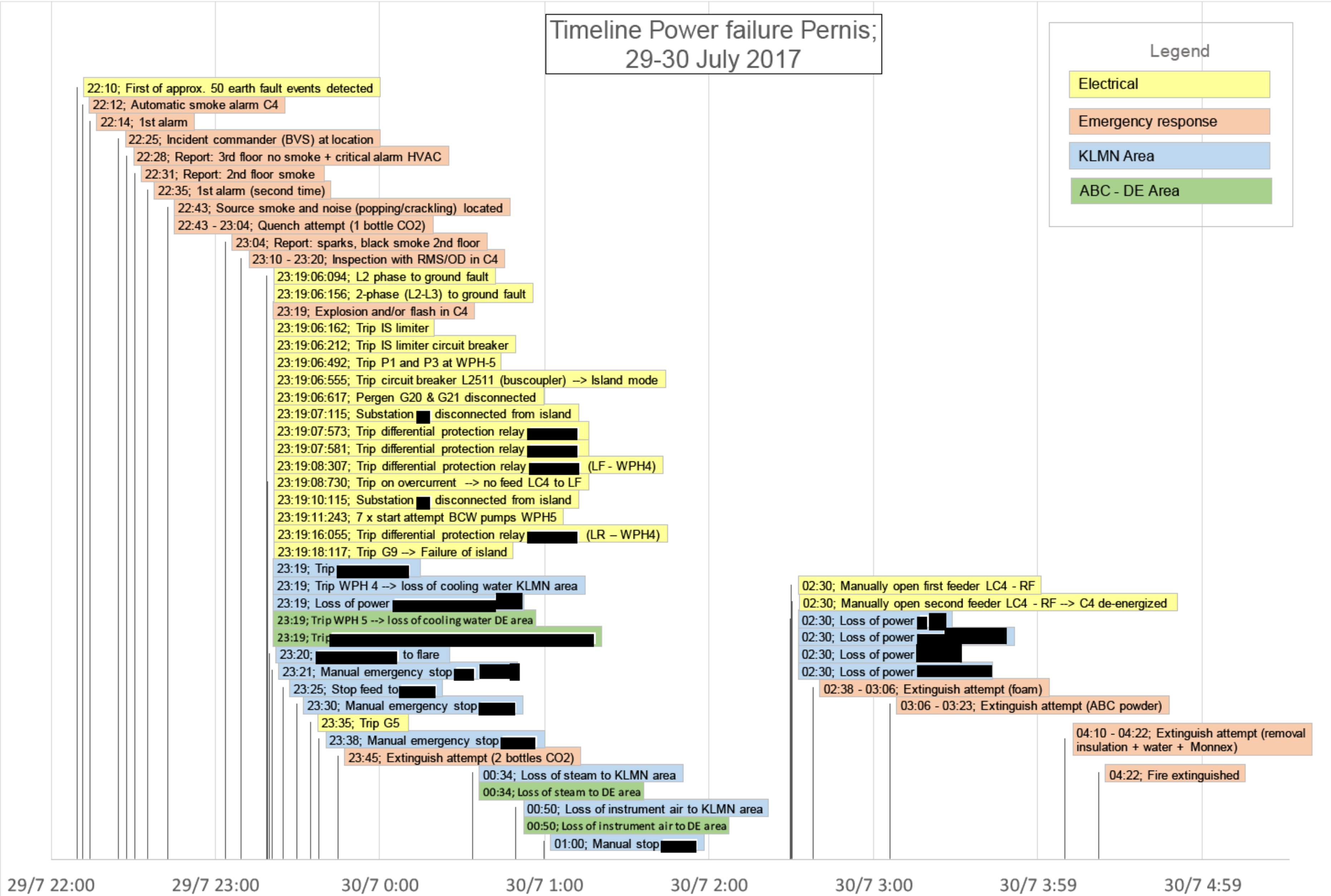
Table 7: Units timeline

EMERGENCY RESPONSE

The main emergency response events that are relevant for the investigation into the bus duct failure, fire and refinery shutdown are described in Table 8.

Date + time	Description of event
29-7-2017 22:12	Automatic smoke alarm Centrale 4 to manned control-room
29-7-2017 22:14	1st Alarm
29-7-2017 22:25	Incident commander from Shell fire brigade at location (Centrale 4)
29-7-2017 22:25 - 22:28	Report fire brigade: no smoke on 3rd floor, on panel critical alarm HVAC and alarm of cabinet 2516
29-7-2017 22:29 - 22:31	Report fire brigade: Visual inspection: 2nd floor smoke and noise (popping/crackling sound) at the location of the 25 kV [redacted] bus duct, behind the perforated coving. Also, alarm on personal EX measurement.
29-7-2017 22:35	1st Alarm (second time)
29-7-2017 22:43	Report fire brigade: source smoke located on second floor. Noise (popping/crackling) and fire phenomena observed at perforated coving (bottom to floor) in right back of building
29-7-2017 22:43 - 23:04	First attempt to quench the perforated coving with CO_2 (1 bottle used)
29-7-2017 23:04	Report fire brigade: in C4 building 2nd floor. In perforated coving. Sparks observed, strong smell, black smoke, heat is up to 1.5 m high
29-7-2017 23:10 - 23:20	Inspection of electrical authority on duty (“A-wacht”) in C4 together with fire department
29-7-2017 23:19	Explosion and/or flash, light flash (orange), door 2nd floor goes from half open to fully open
29-7-2017 23:45	Fireman make exploration round. Second attempt to extinguish the fire (2 bottles of CO_2 used). Observation: perforated coving "gone". Door between east - west opened for ventilation
30-7-2017 2:38	Attempt to extinguish fire using foam
30-7-2017 3:06	Attempt to extinguish fire using ABC powder (dry chemical fire extinguisher) + welding blanket
30-7-2017 4:10	Attempt to extinguish by removing insulation + use of water and monnex powder
30-7-2017 4:22	Fire extinguished

Table 8: Emergency Response timeline


Timeline Power failure Pernis; 29-30 July 2017
Legend
Electrical
Emergency response
KLMN Area
ABC - DE Area
22:10; First of approx. 50 earth fault events detected
22:12; Automatic smoke alarm C4
22:14; 1st alarm
22:25; Incident commander (BVS) at location
22:28; Report: 3rd floor no smoke + critical alarm HVAC
22:31; Report: 2nd floor smoke
22:35; 1st alarm (second time)
22:43; Source smoke and noise (popping/crackling) located
22:43 - 23:04; Quench attempt (1 bottle CO2)
23:04; Report: sparks, black smoke 2nd floor
23:10 - 23:20; Inspection with RMS/OD in C4
23:19:06:094; L2 phase to ground fault
23:19:06:156; 2-phase (L2-L3) to ground fault
23:19; Explosion and/or flash in C4
23:19:06:162; Trip IS limiter
23:19:06:212; Trip IS limiter circuit breaker
23:19:06:492; Trip P1 and P3 at WPH-5
23:19:06:555; Trip circuit breaker L2511 (buscoupler) --> Island mode
23:19:06:617; Pergen G20 & G21 disconnected
23:19:07:115; Substation [redacted] disconnected from island
23:19:07:573; Trip differential protection relay [redacted]
23:19:07:581; Trip differential protection relay [redacted]
23:19:08:307; Trip differential protection relay [redacted] (LF - WPH4)
23:19:08:730; Trip on overcurrent --> no feed LC4 to LF
23:19:10:115; Substation [redacted] disconnected from island
23:19:11:243; 7 x start attempt BCW pumps WPH5
23:19:16:055; Trip differential protection relay [redacted] (LR – WPH4)
23:19:18:117; Trip G9 --> Failure of island
23:19; Trip [redacted]
23:19; Trip WPH 4 --> loss of cooling water KLMN area
23:19; Loss of power [redacted]
23:19; Trip WPH 5 --> loss of cooling water DE area
23:19; Trip [redacted]
23:20; [redacted] to flare
23:21; Manual emergency stop [redacted]
23:25; Stop feed to [redacted]
23:30; Manual emergency stop [redacted]
23:35; Trip G5
23:38; Manual emergency stop [redacted]
23:45; Extinguish attempt (2 bottles CO2)
00:34; Loss of steam to KLMN area
00:34; Loss of steam to DE area
00:50; Loss of instrument air to KLMN area
00:50; Loss of instrument air to DE area
01:00; Manual stop [redacted]
02:30; Manually open first feeder LC4 - RF
02:30; Manually open second feeder LC4 - RF --> C4 de-energized
02:30; Loss of power [redacted]
02:30; Loss of power [redacted]
02:30; Loss of power [redacted]
02:30; Loss of power [redacted]
02:38 - 03:06; Extinguish attempt (foam)
03:06 - 03:23; Extinguish attempt (ABC powder)
04:10 - 04:22; Extinguish attempt (removal insulation + water + Monnex)
04:22; Fire extinguished
29/7 22:00
29/7 23:00
30/7 0:00
30/7 1:00
30/7 2:00
30/7 3:00
30/7 3:59
30/7 4:59

APPENDIX 2. CAUSE & EFFECT DIAGRAM

The letter/number combination in the bottom left corner of each box in the Cause & Effects Diagram in this Appendix is a unique identifier of that cause/effect. More detailed information about several of the boxes in the Cause & Effects Diagram is listed in the tables below. The letter in the bottom right corner indicates the level of quality of these data: F = Fact, H = Hypothesis.

Top event

T	The event took place on the 29th of July and controlled shutdown of the remaining units took place between the 30th of July and 1st of August.

Shutdown ABC Area

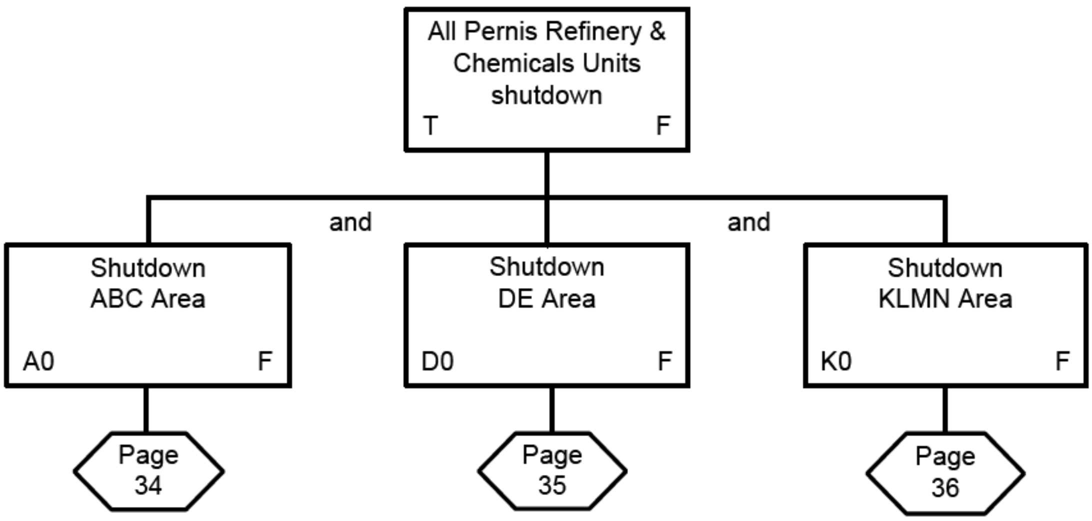
A0	Detailed information about the trips and shutdowns at ABC Area can be found in Appendix 3.
A1	Controlled shutdown of [redacted] units on ABC Area, except for the [redacted].
A33	Exact time is 23:19:07:573 on 29 July.
A34	Exact time is 23:19:07:581 on 29 July.

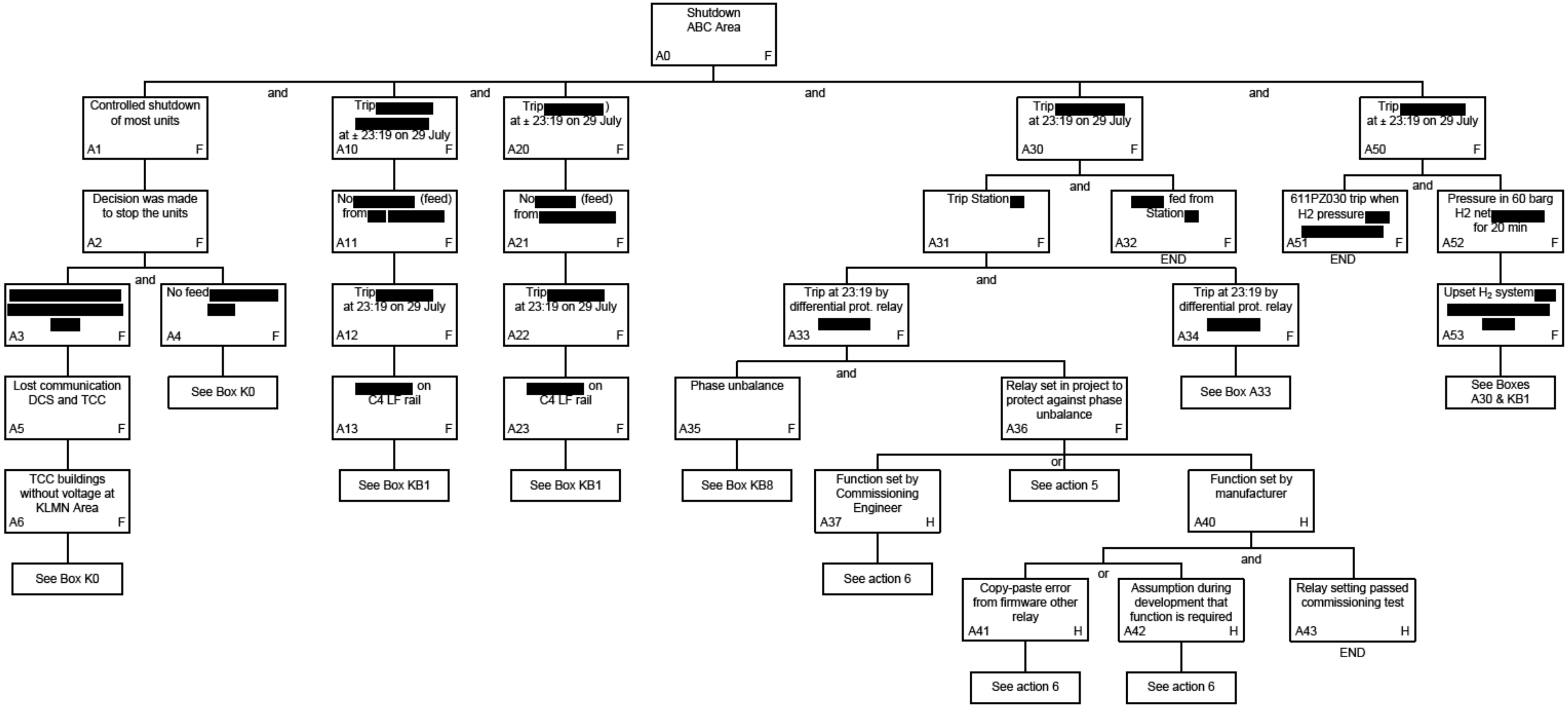
Shutdown DE Area

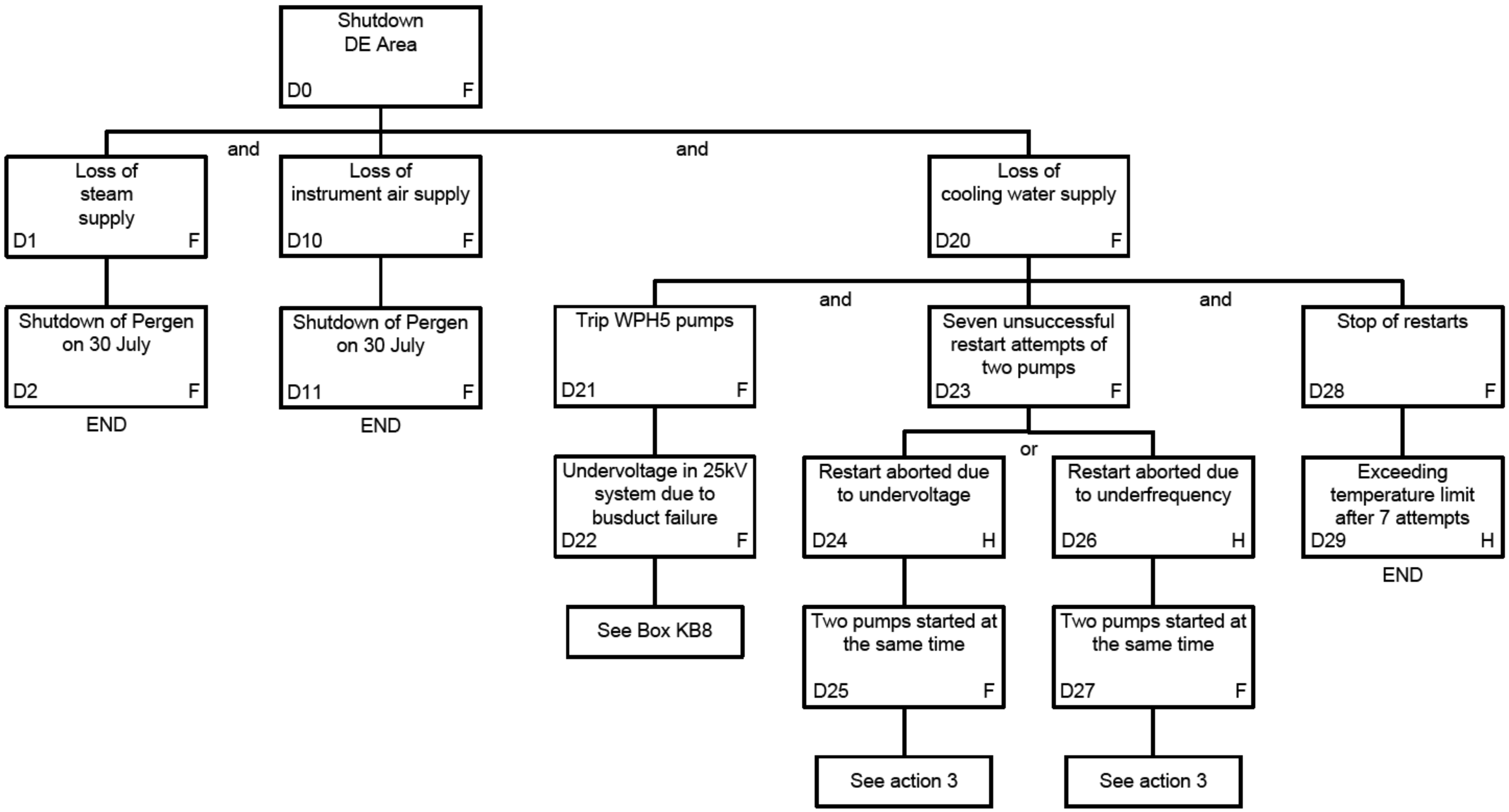
D0	Detailed information about the trips and shutdowns at DE Area can be found in Appendix 3.
D10	[redacted] due to loss of instrument air.
D20	[redacted] due to loss of cooling water supply.

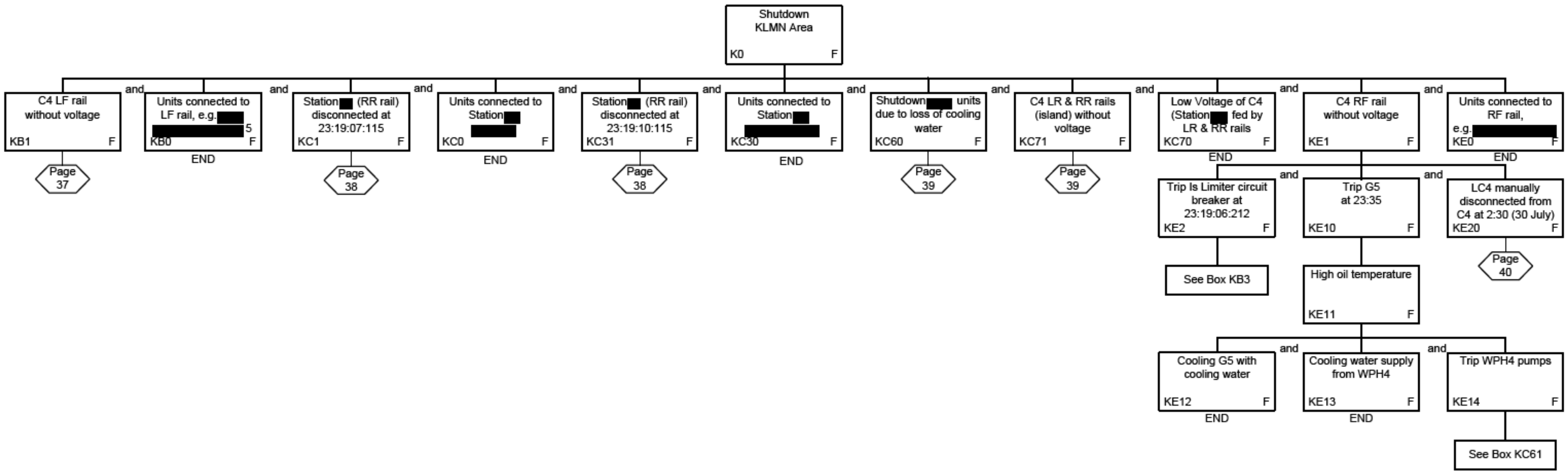
Shutdown KLMN Area

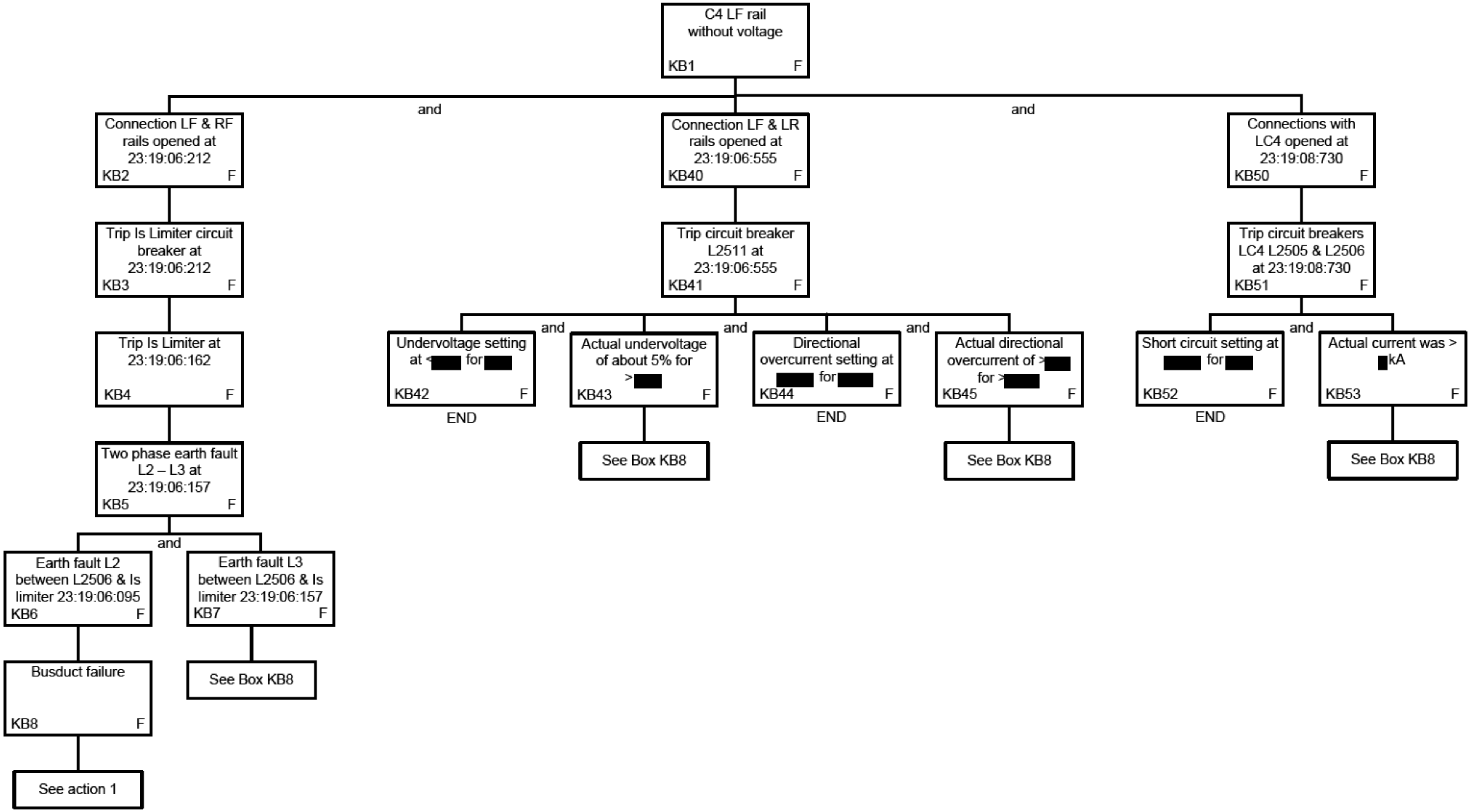
K0	Detailed information about the trips and shutdowns at KLMN Area can be found in Appendix 3.
KB0	Units connected to C4 LF rail were [redacted], WPH4 (pumps were not connected).
KC0	Units connected to Station [redacted] were CD5, HT1, CCR11/14, K4-K9, K11-K14, PK21/22, Quay 30, [redacted]
KC30	Units connected to Station [redacted] were BHC, [redacted]
KC60	The [redacted] units which are tripped due to lack of cooling water can be found in Appendix 3.
KE0	Units connected to C4 RF rail were [redacted]
KB5	Ground fault takes place about 60-70 ms before trip Is Limiter.
KB7	2-phase between L2 and L3. Takes place about 6 ms before trip Is Limiter.
KE48	The design makes it possible to switch on equipment from outside the building, but is an operational choice not to do so.



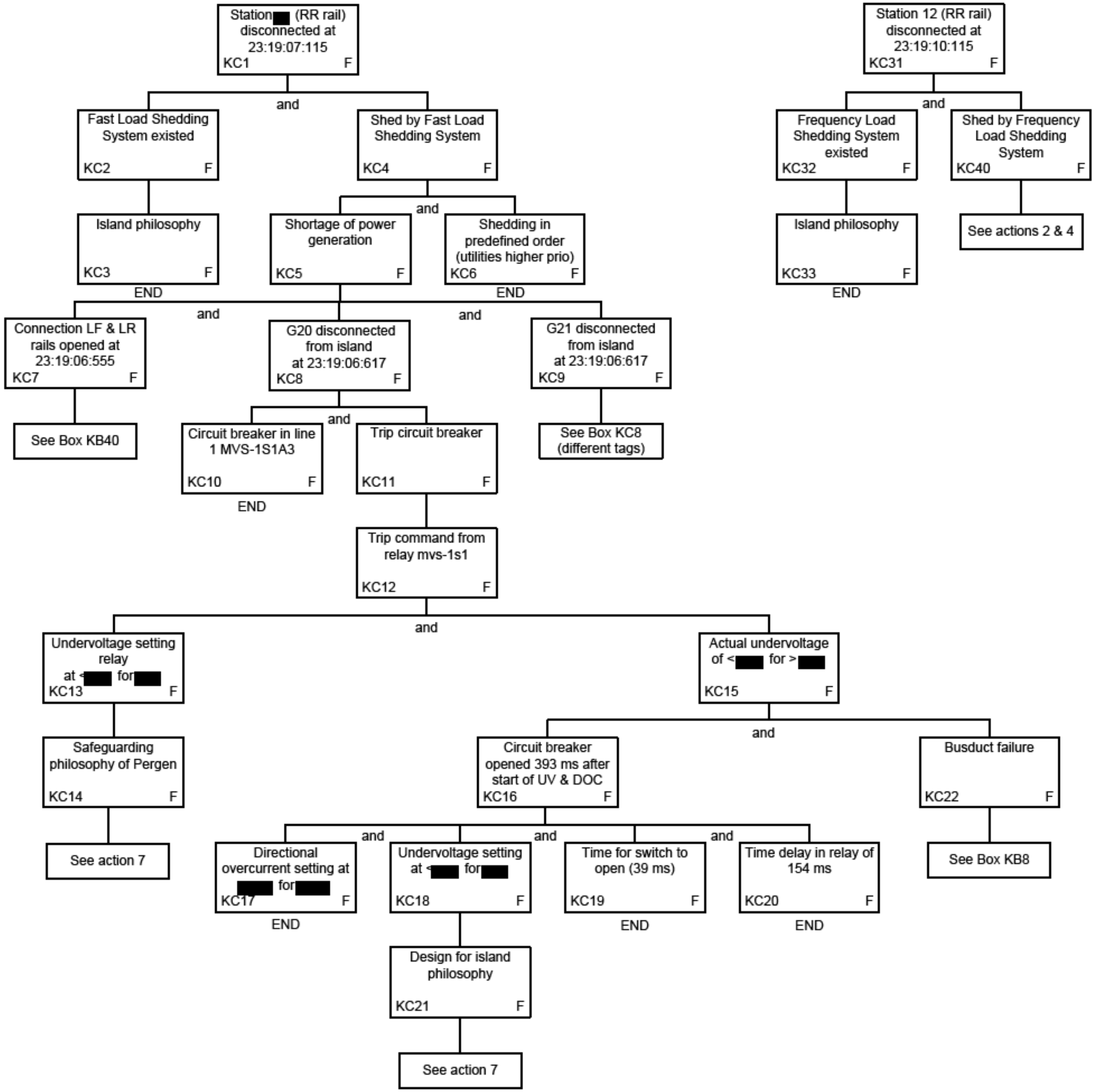

Shutdown ABC Area
A0 F
and
Controlled shutdown of most units
A1 F
Trip [redacted] at ± 23:19 on 29 July
A10 F
Trip [redacted]) at ± 23:19 on 29 July
A20 F
Trip [redacted] at 23:19 on 29 July
A30 F
Trip [redacted] at ± 23:19 on 29 July
A50 F
Decision was made to stop the units
A2 F
No [redacted] (feed) from [redacted]
A11 F
No [redacted] (feed) from [redacted]
A21 F
Trip Station [redacted]
A31 F
[redacted] fed from Station [redacted]
A32 F
END
611PZ030 trip when H2 pressure [redacted]
A51 F
END
Pressure in 60 barg H2 net [redacted] for 20 min
A52 F
[redacted]
A3 F
No feed [redacted]
A4 F
Trip [redacted] at 23:19 on 29 July
A12 F
Trip [redacted] at 23:19 on 29 July
A22 F
Trip at 23:19 by differential prot. relay [redacted]
A33 F
Trip at 23:19 by differential prot. relay [redacted]
A34 F
Upset H_2 system [redacted]
A53 F
Lost communication DCS and TCC
A5 F
See Box K0
[redacted] on C4 LF rail
A13 F
[redacted] on C4 LF rail
A23 F
Phase unbalance
A35 F
Relay set in project to protect against phase unbalance
A36 F
See Box A33
See Boxes A30 & KB1
TCC buildings without voltage at KLMN Area
A6 F
See Box KB1
See Box KB1
See Box KB8
or
Function set by Commissioning Engineer
A37 H
See action 5
Function set by manufacturer
A40 H
See Box K0
See action 6
Copy-paste error from firmware other relay
A41 H
Assumption during development that function is required
A42 H
Relay setting passed commissioning test
A43 H
END
See action 6
See action 6

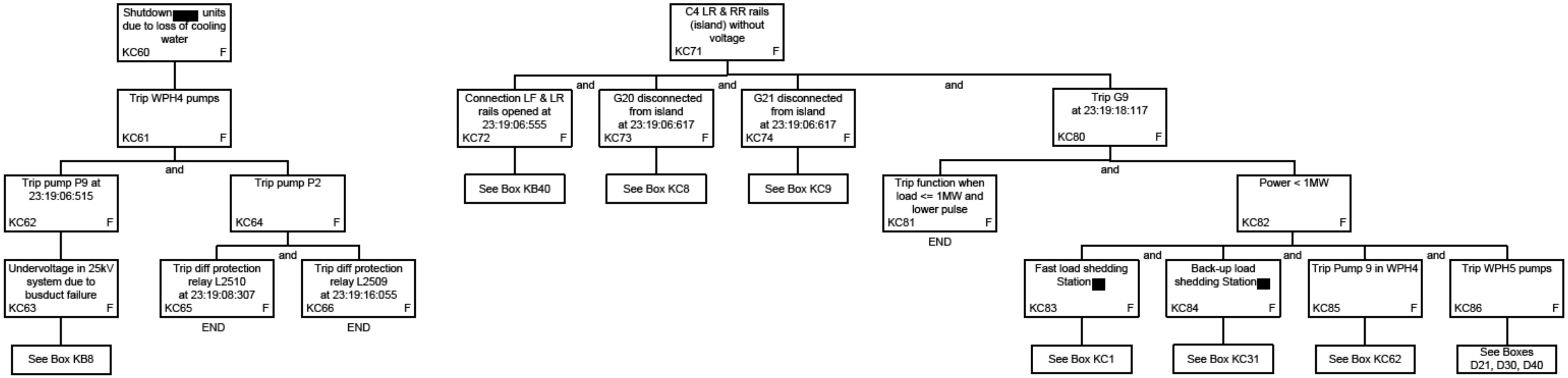

Shutdown
DE Area
D0 F
and
and
Loss of
steam
supply
D1 F
Loss of
instrument air supply
D10 F
Loss of
cooling water supply
D20 F
Shutdown of Pergen
on 30 July
D2 F
END
Shutdown of Pergen
on 30 July
D11 F
END
Trip WPH5 pumps
D21 F
and
Seven unsuccessful
restart attempts of
two pumps
D23 F
and
Stop of restarts
D28 F
Undervoltage in 25kV
system due to
busduct failure
D22 F
or
Restart aborted due
to undervoltage
D24 H
Restart aborted due
to underfrequency
D26 H
Exceeding
temperature limit
after 7 attempts
D29 H
END
See Box KB8
Two pumps started at
the same time
D25 F
Two pumps started at
the same time
D27 F
See action 3
See action 3

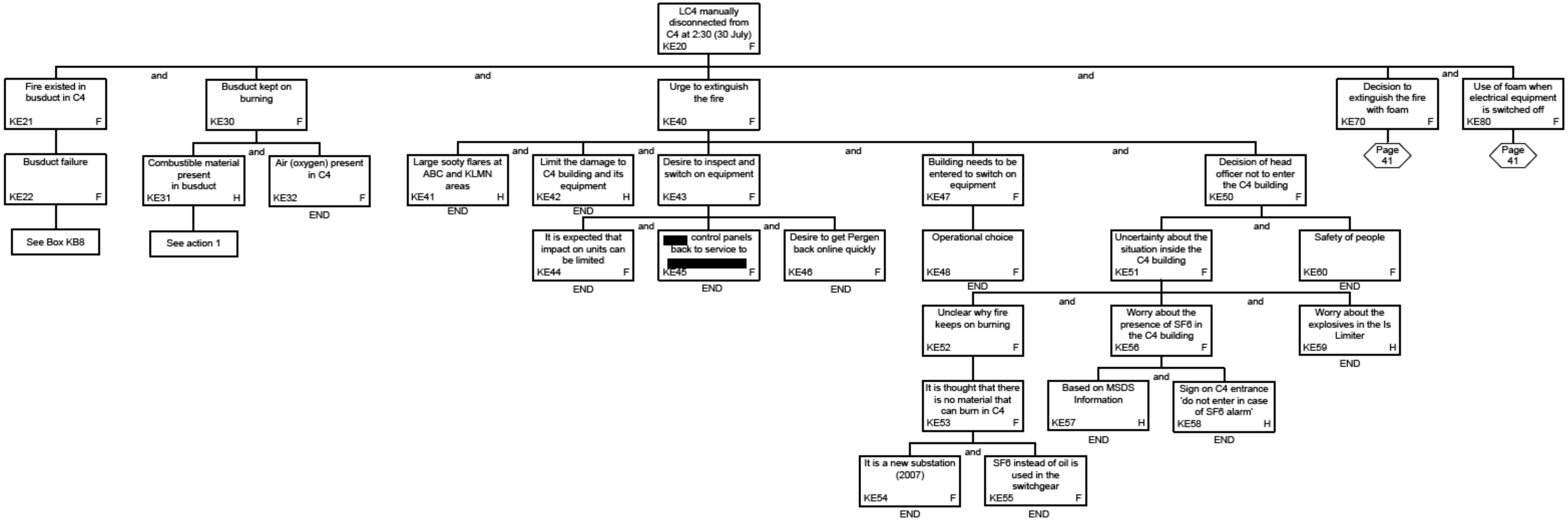

Shutdown KLMN Area
K0 F
and
C4 LF rail without voltage
KB1 F
Page 37
Units connected to LF rail, e.g. [redacted] 5
KB0 F
END
Station [redacted] (RR rail) disconnected at 23:19:07:115
KC1 F
Page 38
Units connected to Station [redacted]
KC0 F
END
Station [redacted] (RR rail) disconnected at 23:19:10:115
KC31 F
Page 38
Units connected to Station [redacted]
KC30 F
END
Shutdown [redacted] units due to loss of cooling water
KC60 F
Page 39
C4 LR & RR rails (island) without voltage
KC71 F
Page 39
Low Voltage of C4 (Station [redacted] fed by LR & RR rails
KC70 F
END
C4 RF rail without voltage
KE1 F
Units connected to RF rail, e.g. [redacted]
KE0 F
END
Trip Is Limiter circuit breaker at 23:19:06:212
KE2 F
See Box KB3
Trip G5 at 23:35
KE10 F
High oil temperature
KE11 F
LC4 manually disconnected from C4 at 2:30 (30 July)
KE20 F
Page 40
Cooling G5 with cooling water
KE12 F
END
Cooling water supply from WPH4
KE13 F
END
Trip WPH4 pumps
KE14 F
See Box KC61

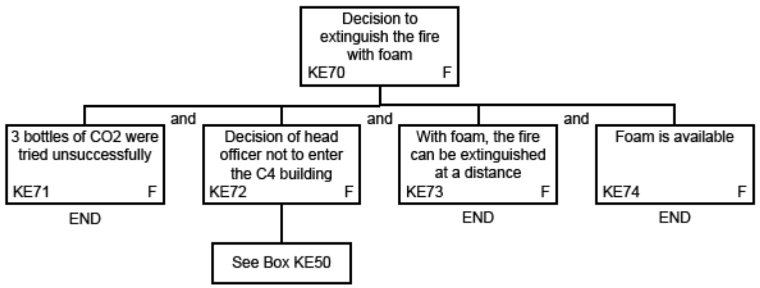


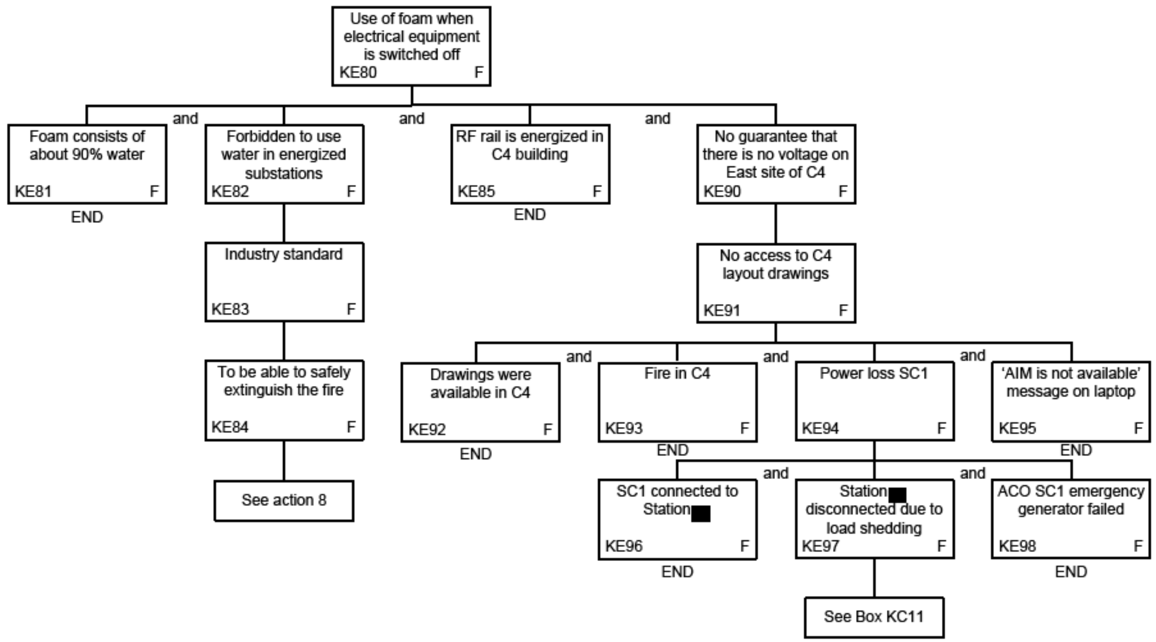
C4 LF rail without voltage KB1 F
and
and
Connection LF & RF rails opened at 23:19:06:212 KB2 F
Connection LF & LR rails opened at 23:19:06:555 KB40 F
Connections with LC4 opened at 23:19:08:730 KB50 F
Trip Is Limiter circuit breaker at 23:19:06:212 KB3 F
Trip circuit breaker L2511 at 23:19:06:555 KB41 F
Trip circuit breakers LC4 L2505 & L2506 at 23:19:08:730 KB51 F
Trip Is Limiter at 23:19:06:162 KB4 F
and
and
and
and
Undervoltage setting at <[redacted] for [redacted] KB42 F
END
Actual undervoltage of about 5% for >[redacted] KB43 F
Directional overcurrent setting at [redacted] for [redacted] KB44 F
END
Actual directional overcurrent of >[redacted] for >[redacted] KB45 F
Short circuit setting at [redacted] for [redacted] KB52 F
END
Actual current was > [redacted] kA KB53 F
See Box KB8
See Box KB8
See Box KB8
Two phase earth fault L2 – L3 at 23:19:06:157 KB5 F
and
Earth fault L2 between L2506 & Is limiter 23:19:06:095 KB6 F
Earth fault L3 between L2506 & Is limiter 23:19:06:157 KB7 F
Busduct failure KB8 F
See Box KB8
See action 1


Station [redacted] (RR rail) disconnected at 23:19:07:115 KC1 F
and
Fast Load Shedding System existed KC2 F
Island philosophy KC3 F
END
Shed by Fast Load Shedding System KC4 F
and
Shortage of power generation KC5 F
Shedding in predefined order (utilities higher prio) KC6 F
END
and
Connection LF & LR rails opened at 23:19:06:555 KC7 F
See Box KB40
G20 disconnected from island at 23:19:06:617 KC8 F
and
G21 disconnected from island at 23:19:06:617 KC9 F
See Box KC8 (different tags)
Circuit breaker in line 1 MVS-1S1A3 KC10 F
END
Trip circuit breaker KC11 F
Trip command from relay mvs-1s1 KC12 F
and
Undervoltage setting relay at <[redacted] for [redacted] KC13 F
Safeguarding philosophy of Pergen KC14 F
See action 7
Actual undervoltage of <[redacted] for >[redacted] KC15 F
and
Circuit breaker opened 393 ms after start of UV & DOC KC16 F
Busduct failure KC22 F
See Box KB8
and
and
and
Directional overcurrent setting at [redacted] for [redacted] KC17 F
END
Undervoltage setting at <[redacted] for [redacted] KC18 F
Design for island philosophy KC21 F
See action 7
Time for switch to open (39 ms) KC19 F
END
Time delay in relay of 154 ms KC20 F
END
Station 12 (RR rail) disconnected at 23:19:10:115 KC31 F
and
Frequency Load Shedding System existed KC32 F
Island philosophy KC33 F
END
Shed by Frequency Load Shedding System KC40 F
See actions 2 & 4


Shutdown [redacted] units due to loss of cooling water
KC60 F
Trip WPH4 pumps
KC61 F
and
Trip pump P9 at 23:19:06:515
KC62 F
Trip pump P2
KC64 F
Undervoltage in 25kV system due to busduct failure
KC63 F
See Box KB8
and
Trip diff protection relay L2510 at 23:19:08:307
KC65 F
END
Trip diff protection relay L2509 at 23:19:16:055
KC66 F
END
C4 LR & RR rails (island) without voltage
KC71 F
and
and
and
Connection LF & LR rails opened at 23:19:06:555
KC72 F
See Box KB40
G20 disconnected from island at 23:19:06:617
KC73 F
See Box KC8
G21 disconnected from island at 23:19:06:617
KC74 F
See Box KC9
Trip G9 at 23:19:18:117
KC80 F
and
Trip function when load <= 1MW and lower pulse
KC81 F
END
Power < 1MW
KC82 F
and
and
and
Fast load shedding Station [redacted]
KC83 F
See Box KC1
Back-up load shedding Station [redacted]
KC84 F
See Box KC31
Trip Pump 9 in WPH4
KC85 F
See Box KC62
Trip WPH5 pumps
KC86 F
See Boxes D21, D30, D40


LC4 manually disconnected from C4 at 2:30 (30 July) KE20 F
and
Fire existed in busduct in C4 KE21 F
Busduct failure KE22 F
See Box KB8
Busduct kept on burning KE30 F
Combustible material present in busduct KE31 H
See action 1
Air (oxygen) present in C4 KE32 F
END
Urge to extinguish the fire KE40 F
Large sooty flares at ABC and KLMN areas KE41 H
END
Limit the damage to C4 building and its equipment KE42 H
END
Desire to inspect and switch on equipment KE43 F
It is expected that impact on units can be limited KE44 F
END
[redacted] control panels back to service to [redacted] KE45 F
END
Desire to get Pergen back online quickly KE46 F
END
Building needs to be entered to switch on equipment KE47 F
Operational choice KE48 F
END
Decision of head officer not to enter the C4 building KE50 F
Uncertainty about the situation inside the C4 building KE51 F
Unclear why fire keeps on burning KE52 F
It is thought that there is no material that can burn in C4 KE53 F
It is a new substation (2007) KE54 F
END
SF6 instead of oil is used in the switchgear KE55 F
END
Worry about the presence of SF6 in the C4 building KE56 F
Based on MSDS Information KE57 H
END
Sign on C4 entrance 'do not enter in case of SF6 alarm' KE58 H
END
Worry about the explosives in the Is Limiter KE59 H
END
Safety of people KE60 F
END
Decision to extinguish the fire with foam KE70 F
Page 41
Use of foam when electrical equipment is switched off KE80 F
Page 41


Decision to extinguish the fire with foam
KE70 F
and
3 bottles of CO2 were tried unsuccessfully
KE71 F
END
Decision of head officer not to enter the C4 building
KE72 F
See Box KE50
With foam, the fire can be extinguished at a distance
KE73 F
END
Foam is available
KE74 F
END


Use of foam when electrical equipment is switched off
KE80 F
and
Foam consists of about 90% water
KE81 F
END
Forbidden to use water in energized substations
KE82 F
Industry standard
KE83 F
To be able to safely extinguish the fire
KE84 F
See action 8
RF rail is energized in C4 building
KE85 F
END
No guarantee that there is no voltage on East site of C4
KE90 F
No access to C4 layout drawings
KE91 F
Drawings were available in C4
KE92 F
END
Fire in C4
KE93 F
END
Power loss SC1
KE94 F
'AIM is not available' message on laptop
KE95 F
END
SC1 connected to Station [redacted]
KE96 F
END
Station [redacted] disconnected due to load shedding
KE97 F
See Box KC11
ACO SC1 emergency generator failed
KE98 F
END

APPENDIX 3. TRIPS & SHUTDOWN

In this Appendix, an overview is given of what happened to each unit in Pernis. In line with the Cause & Effect diagram, this analysis is done per area on the Pernis site: ABC, DE and KLMN.

ABC AREA

In Table 9, all units on the ABC Area are listed. In the Table the approximate time at which the shutdown was started is given and the reason for shutdown. As can be derived from this Table, most the units on the ABC Area had a controlled slowdown and shutdown. The exceptions are indicated in red: [redacted]. The details of these trips are discussed in the section 'Outcome'.

PU	Unit	Approximate start shutdown	Reason for shutdown
[redacted]	[redacted]	30-7-2017 20:45	Controlled shutdown
[redacted]	[redacted]	30-7-2017 19:00	Controlled shutdown
[redacted]	[redacted]	1-8-2017 11:00	Controlled shutdown
[redacted]	[redacted]	29-7-2017 23:19	Trip due to loss of power
RHP	PGP	N/A	Not shutdown (power generation plant)
RHP	WPH-3	N/A	Not shutdown (cooling water)
[redacted]	[redacted]	30-7-2017 21:20	Controlled shutdown
[redacted]	[redacted]	31-7-2017 3:30	Controlled shutdown, unit for unit start 31-7 3:30 h
[redacted]	[redacted]	30-7-2017 11:30	Controlled shutdown
[redacted]	[redacted]	29-7-2017 23:19	Trip due to loss of feed [redacted]
[redacted]	[redacted]	1-8-2017 8:30	Controlled shutdown
[redacted]	[redacted]	29-7-2017 23:19	Trip due to loss of LM [redacted]
[redacted]	[redacted]	30-7-2017 1:45	Controlled shutdown, unit for unit starting 30-7 1:45 h
[redacted]	[redacted]	31-7-2017 01:00	Controlled reduction
[redacted]	[redacted]	31-7-2017 6:00	Controlled shutdown
[redacted]	[redacted]	30-7-2017 8:00	Controlled shutdown
[redacted]	[redacted]	30-7-2017 24:00	Controlled shutdown
[redacted]	[redacted]	30-7-2017 11:30	Controlled shutdown
[redacted]	[redacted]	30-7-2017 20:50	Controlled shutdown
RVC	Heavy slops	N/A	Unit not in service due to planned maintenance
[redacted]	[redacted]	30-7-2017 12:30	Controlled in circulation mode
[redacted]	[redacted]	31-7-2017 15:30	Controlled shutdown
RWH	RWZ	N/A	Unit (water treatment) kept in operation at a reduced mode
[redacted]	[redacted]	29-7-2017 23:19	Trip unit due to low hydrogen pressure
[redacted]	[redacted]	30-7-2017 21:00	Controlled in circulation mode

Table 9: Trips & shutdown of units on ABC Area

DE AREA

On the DE Area of the site, most Shell units stopped due to failure of utilities: cooling water, steam and instrument air, as can be seen in Table 10.

PU	Unit	Approximate time shutdown	Lost Utility	Reason for shutdown
[redacted]	[redacted]	29-7-2017 23:20	Cooling water	Unit put on circulation mode
[redacted]	[redacted]	29-7-2017 23:19	Cooling water	Reactors were empty, no new batch started
CVP	Sannest	N/A	N/A	This unit was not in service due to planned maintenance.
[redacted]	[redacted]	29-7-2017 23:19 30-7-2017 0:50	Power Instrument air	Stop Mixer [redacted] restart was possible Batch on hold
[redacted]	[redacted]	29-7-2017 23:19	Cooling water	Trip unit
RWH	CWZ	N/A	N/A	Initial trip of some pump, could be restarted. Unit kept running at reduced throughput
[redacted]	[redacted]	29-7-2017 23:19	Power	

Table 10: Trips & shutdown of Shell units on DE Area

KLMN AREA

For the KLMN Area the impact for each PU was different. For that reason, a table is made for each PU. Tables 11, 12 and 13 indicate which unit was connected to which rail in C4 at the start-of the incident and why the unit tripped.

All [redacted] units tripped around 23:19 h due to power failure. As they were already tripped, failure of the other utilities (cooling water, steam, instrument air) did not have additional impact.

PU	Unit	Rail C4 + substation	Date + time trip	Reason trip
[redacted]	[redacted]	[redacted]	29-7-2017 23:19	Loss of power
[redacted]	[redacted]	[redacted]	29-7-2017 23:19	Loss of power
[redacted]	[redacted]	[redacted]	29-7-2017 23:19	Loss of power
[redacted]	[redacted]	[redacted]	29-7-2017 23:19	Loss of power
[redacted]	[redacted]	[redacted]	29-7-2017 23:19	Loss of power
[redacted]	[redacted]	[redacted]	29-7-2017 23:19	Loss of power
[redacted]	[redacted]	[redacted]	29-7-2017 23:19	Loss of power
[redacted]	[redacted]	[redacted]	29-7-2017 23:19	Loss of power
[redacted]	[redacted]	[redacted]	29-7-2017 23:19	Loss of power
[redacted]	[redacted]	[redacted]	29-7-2017 23:19	Loss of power
[redacted]	[redacted]	[redacted]	29-7-2017 23:19	Loss of power
[redacted]	[redacted]	[redacted]	29-7-2017 23:19	Loss of power
[redacted]	[redacted]	[redacted]	29-7-2017 23:19	Loss of power

Table 11: Trips & shutdown of RDU units (KLMN Area)

ROM is scattered over the full KLMN Area and for that reason Table 12 shows which tanks, pumps and buildings were connected to which substation and rail in Centrale 4.

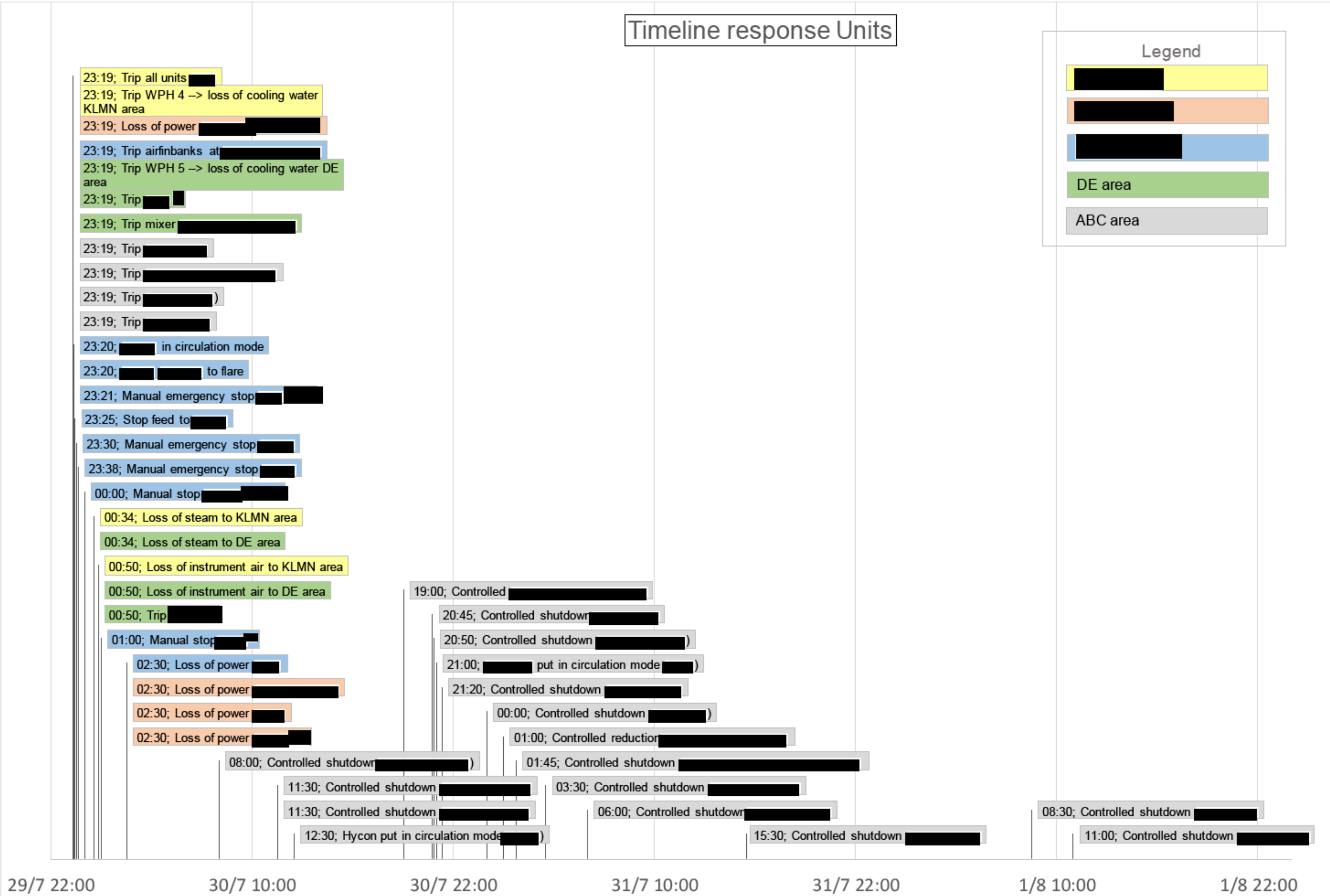
PU	Rail C4 + substation	Time loss of power	Equipment connected
[redacted]	[redacted]	29-7-2017 23:19	[redacted]
[redacted]	[redacted]	29-7-2017 23:19	[redacted]
[redacted]	[redacted]	29-7-2017 23:19	[redacted]
[redacted]	[redacted]	30-7-2017 2:30	[redacted]

Table 12: Trips & shutdown of ROM (KLMN Area)

COD is also present at the KLMN Area. In contrast with the [redacted] units, the [redacted] units did not lose power immediately but at 30-7-2017 2:30 h. However, the [redacted] units did lose utilities: cooling water at 23:19 h, steam at 0:34 and instrument air at 0:50 h. Table 13 below shows why each unit stopped.

PU	Unit	Rail C4 + substation	Date + time trip	Lost utility	First action
[redacted]	[redacted]	[redacted]	29-7-2017 23:20	Cooling water	Manual action → reactors to flare
[redacted]	[redacted]	[redacted]	29-7-2017 23:21	Cooling water	Manual emergency stop
[redacted]	[redacted]	[redacted]	29-7-2017 23:23	Cooling water	Stop feed to unit
[redacted]	[redacted]	[redacted]	29-7-2017 23:30	Cooling water	Manual emergency stop
[redacted]	[redacted]	[redacted]	29-7-2017 23:19 29-7-2017 23:38	Power Cooling water	Trip air fin banks [redacted] → restart was possible Manual emergency stop
[redacted]	[redacted]	[redacted]	29-7-2017 23:23 30-7-2017 01:00	Cooling water Instrument air	Manual stop [redacted] Manual stop [redacted]
[redacted]	[redacted]	[redacted]	29-7-2017 23:19 30-7-2017 0:50	Power Instrument air	Trip VRU U1900 → restart possible Trip VRU (also Jetty 35+35A)

Table 13: Trips & shutdown of COD units (KLMN Area)


Timeline response Units
Legend
[redacted]
[redacted]
[redacted]
DE area
ABC area
23:19; Trip all units [redacted]
23:19; Trip WPH 4 --> loss of cooling water KLMN area
23:19; Loss of power [redacted]
23:19; Trip airfinbanks at [redacted]
23:19; Trip WPH 5 --> loss of cooling water DE area
23:19; Trip [redacted]
23:19; Trip mixer [redacted]
23:19; Trip [redacted]
23:19; Trip [redacted]
23:19; Trip [redacted])
23:19; Trip [redacted]
23:20; [redacted] in circulation mode
23:20; [redacted] to flare
23:21; Manual emergency stop [redacted]
23:25; Stop feed to [redacted]
23:30; Manual emergency stop [redacted]
23:38; Manual emergency stop [redacted]
00:00; Manual stop [redacted]
00:34; Loss of steam to KLMN area
00:34; Loss of steam to DE area
00:50; Loss of instrument air to KLMN area
00:50; Loss of instrument air to DE area
00:50; Trip [redacted]
01:00; Manual stop [redacted]
02:30; Loss of power [redacted]
02:30; Loss of power [redacted]
02:30; Loss of power [redacted]
02:30; Loss of power [redacted]
08:00; Controlled shutdown [redacted])
11:30; Controlled shutdown [redacted]
11:30; Controlled shutdown [redacted]
12:30; Hycon put in circulation mode [redacted])
19:00; Controlled [redacted]
20:45; Controlled shutdown [redacted]
20:50; Controlled shutdown [redacted])
21:00; [redacted] put in circulation mode [redacted])
21:20; Controlled shutdown [redacted]
00:00; Controlled shutdown [redacted])
01:00; Controlled reduction [redacted]
01:45; Controlled shutdown [redacted]
03:30; Controlled shutdown [redacted]
06:00; Controlled shutdown [redacted]
15:30; Controlled shutdown [redacted]
08:30; Controlled shutdown [redacted]
11:00; Controlled shutdown [redacted]
29/7 22:00
30/7 10:00
30/7 22:00
31/7 10:00
31/7 22:00
1/8 10:00
1/8 22:00

APPENDIX 4. OVERVIEW PERNIS ELECTRICAL MAIN INFRASTRUCTURE

Shell Pernis has its own electrical distribution system with connections to the public grid, as is illustrated in Figure 20. The point of connection with the public grid is Centrale 3 on 66 kV voltage level to which two generators (G13 and G14) feed in. Centrale 2 (25 kV) is connected to Centrale 3 and feeds the [redacted] Area, [redacted]. Three generators (G9, G11 and G12) feed in on Centrale 2. Load Centre 4 (25 kV) feeds the [redacted] Area including [redacted] Area. Centrale 4 (25 kV) is connected to Load Center 4 feeding [redacted]. Four generators (G5, G9, G20 and G21) feed in on Centrale 4 of which three are from Pergen (G5, G20 and G21). All HV substations (approx. 100) on 25 kV, 6 kV and 3 kV, hence all 65 plants, are connected to this main electrical infrastructure. The total capacity of the distribution system is approx. 200 MW.

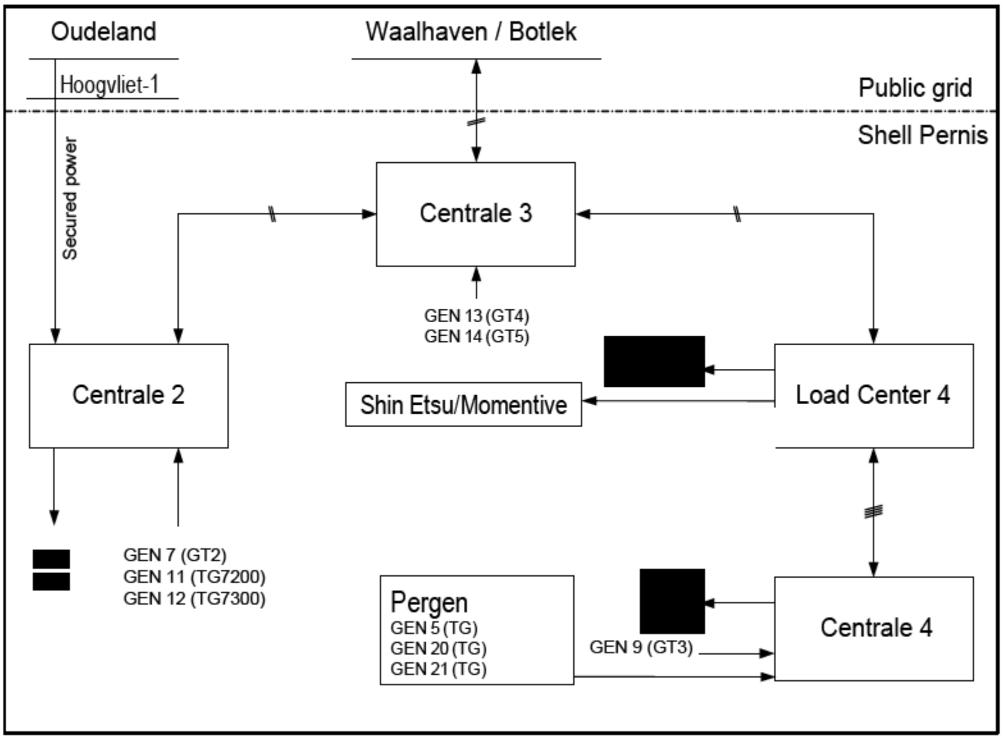


Fig.20: Overview main distribution network Shell Pernis

Figure 21 shows a detailed overview of the Centrale 3, Load Centre 4 and Centrale 4 connection.

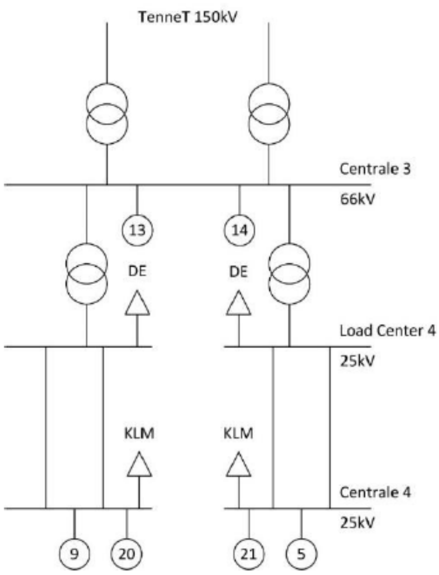


Fig.21: Detailed overview Centrale 3, Load Centre 4 and Centrale 4

APPENDIX 5. BUS DUCT IN 25 KV SWITCHGEAR

The [redacted] bus duct system is making the connection between the Left-hand side of the 25 kV switchgear in Centrale 4 and the Right-hand side of the 25 kV switchgear in Centrale 4. With bus bar selection switches a selection can be made to either make the connection between the Left Front, Left Rear switchgear sections to the Right Front or Right Rear switchgear section. This connection is made via an Is-limiter. Due to the significant power generation and in feeding transformers the high short circuit exceeds the short circuit breaking capacity of the switchgear. For this reason, an Is-limiter is installed that as soon as a short circuit is recognized the Left-hand side is separated from the Right-hand side reducing the short circuit current to a level that the circuit breakers can switch off the short circuit.

The [redacted] Bus bar system consists of a copper conductor insulated with cast resin impregnated paper layers with several layers to control the stress. The system is rated at 2500 A and 36 kV although it is operated at 25 kV with a normal current loading of less than 500 A. The manufacturing length and shape is determined by the oven at the manufacturing location. Because the required length and shape at Centrale 4 is different than what can be manufactured at [redacted] (flexible) connections are required to be made at Centrale 4 during installation. More information can be found in Figure 22 which contains a brochure about the [redacted] Bus bar system.

[redacted]

Fig.22: Brochure [redacted] Bus bar system

APPENDIX 6. ABBREVIATIONS

[redacted]	[redacted]
ABC Area	East side of the Pernis Refinery
A-wacht	Electrical authority on duty
BHC	Benzene Heart-cut Splitter (Unit)
C4	Centrale 4
CCR	Control room Refinery
CD	Crude Distiller (Unit)
CED	Cause & Effect Diagram
CIN	Centraal Incidenten Nummer
COD	Chemicals Solvents (“Oplosmiddelen”) and Derivatives (1 out of 8 production units)
COF	Chemie Oplosmiddelen fabriek (unit)
COPI	COmmand Place Incident
CT	Current Transformer
CVP	Chemicals Loading (“Verladingen”) and Polyols (1 out of 8 production units)
CWZ	Water treatment unit
DCS	Distributed control system (Control system used to operate the units from the control room)
DE Area	Area between the ABC and KLMN Areas
DOC	Directional Overcurrent
ENMC	Electrical Network Monitoring and Control
G	Generator
GRIP	Coordinated Regional Incident control Procedure
HDS	Hydro desulphurization unit
HGU	Hydrogenation unit
HK	Office building
HT	Hydro treater (unit)
KEGROB	Kontactgroep Electrotechniek Grote Bedrijven
KLMN Area	West side of the Pernis Refinery
LC4	Load Center 4
LF	Left Front
LR	Left Rear
MBU	Membrane unit
OEM	Original Equipment Manufacturer
OIC	Observation – Insight – Conclusion (learning session)
PIT	Product in Tank
PK	Pump room
prot	Protection
PSSR	Pre Start-up Safety Review
RDU	Refinery Distillation Utilities (1 out of 8 production units)
RF	Right Front
RHP	Refinery Hydro- & thermal cracking, gasification & Powerplant (1 out of 8 production units)
RMS/OD	Electrical department, see also “A-wacht”
ROM	Refinery Oil Movements (1 out of 8 production units)
RR	Right Rear
RTA	Refinery Treating and Alkylation (1 out of 8 production units)
RVC	Refinery Vacuum and Conversion (1 out of 8 production units)
RWH	Refinery Water-treatment, flaring, SARU & Hycon (1 out of 8 production units)
SBP	Special boiling-point unit (unit)
SC	Service Center (office building)
SNR	Shell Nederland Raffinaderij
SoF	Statement of Fitness
TR	Transformer
TS	Substation
UV	Undervoltage
VNCI	Vereniging Nederlandse Chemische Industrie
VNPI	Vereniging Nederlandse Petroleum Industrie
WPH	Water Pump House