Curacao Blackout Investigations Review

20/02/2024

Prepared for BT&P

In the framework of
WBS SPO18824

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Curacao Blackout Investigations Review

Version number	Date	Description and modification history
v1	20/02/2024	New report (draft).
v2	15 February 2024	Final report (integrating feedback from Aqualectra)

Contents

1. Introduction

1.1. Context

Curacao experienced multiple blackouts in 2019-2021. Recently, after a relatively stable period, another two blackouts occurred in the summer of 2023 which caused political pressure and a strong demand for thorough investigations. During these investigations, again a blackout occurred in November 2023. This last blackout is not considered in the study.

As the utility company Aqualectra initiated multiple studies/assessments with known consultancy firms DNV GL and DigSilent, the decision was made not to redo the work already done, but to independently review the reports made by these firms to address the call for an independent investigation. The goal is to check whether the reports and the defined actions are adequate, complete, and already taken or planned for effectively. In order to do so, the Minister has formally instructed Aqualectra, in addition to the current Concession obligations, to cooperate fully and to support the investigation by all means. The investigation will be coordinated by the regulatory body BT&P.

1.2. Purpose of the investigation

As the investigation will primarily focus on work already done, the main activity is to review the documents (made) available. No simulations, contact with manufacturers, tests, etc. are foreseen. However, limited contact with key Aqualectra personnel needs to be taken into account. It will be needed to address question marks related to the documentation and to verify draft conclusions before the final report is submitted.

The procedure followed during the investigation is given in Figure 1. It can be seen that the investigations reports (from DNV or DigSilent) are used as basis of the investigations[1]. Letters between Aqualectra and BT&P are also analyzed as they contain valuable information. In a second phase, additional documents are analyzed in order to go deeper into the three following main topics (i) protection, (ii) power generation & stability, and (iii) organization procedure.

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[1] *Starting point of the investigation was limited to the available reports and conclusions at the time the project was initated (sep 2023).*

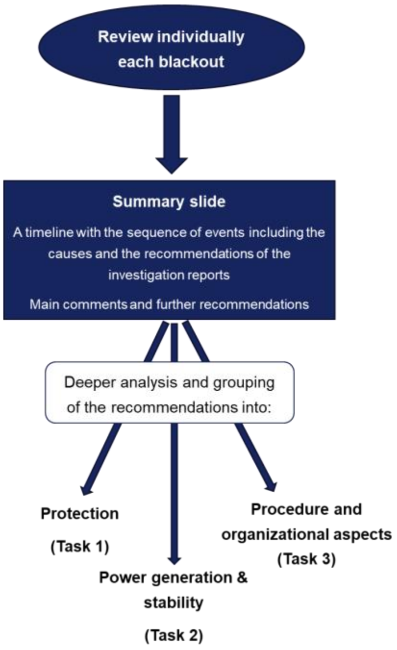


Figure 1 - Methodology for investigating the blackouts

1.3. Structure

The document is structured as follows. First, the blackout investigation reports are analyzed and summarized in the next chapter. Then, dedicated sections take place focusing on (i) protection aspects, (ii) power generation and stability (including voltage and frequency management) and (iii) organization and procedures. Finally, conclusions and recommendations are provided.

2. Task 0: analysis of the blackout reports

In this chapter, the blackout reports provided are analyzed and summarized as illustrated in Figure 1. For each blackout, the summarized view contains:

- The reference documents used
- A timeline with the sequence of events including the causes and the recommendations of the investigation reports
- Additionally for each event:
    - Our remarks regarding the explanation/description of the event in the reports
    - General comments on the investigation itself
    - Our comments on the recommendations and additional further actions

Our main comments on the investigations that have been performed in the past are:

- **The investigation reports follow a sound approach and are from our point of view technically correct.** For example, the observations on protection settings are correct and it is justified to improve the settings and protection philosophy.
- **Follow-up of recommendations and current status not always clearly tracked.** For example, recommendations from the DigSilent 2014 report on RES integration are numerous and relevant but it is unclear whether these have been implemented.
- The scope of work of the blackout investigations **is from our point of view too narrow**, focusing only at technical facts. Some of the limitations of the investigation reports are listed hereafter:
    - None of the reports confirms or not whether the initial operating point (i.e. before the event) was acceptable in terms of security (e.g. N-1 secure)
    - None of the reports show a replication of the events using simulations.
    - Timing for the investigations and implementation of the actions. For example, if investigations of December blackouts 2020 had been faster, this would most likely have avoided the January 2021 blackout.
    - Restoration aspects are not covered.

After analysis of the blackout report, it is proposed to group the main causes of blackouts into three categories: (i) protection, (ii) power generation and stability, and (iii) organization and procedure. The main causes of blackout can be seen in Figure 2 and as it can be observed, blackouts are generally caused by a combination of these main causes.

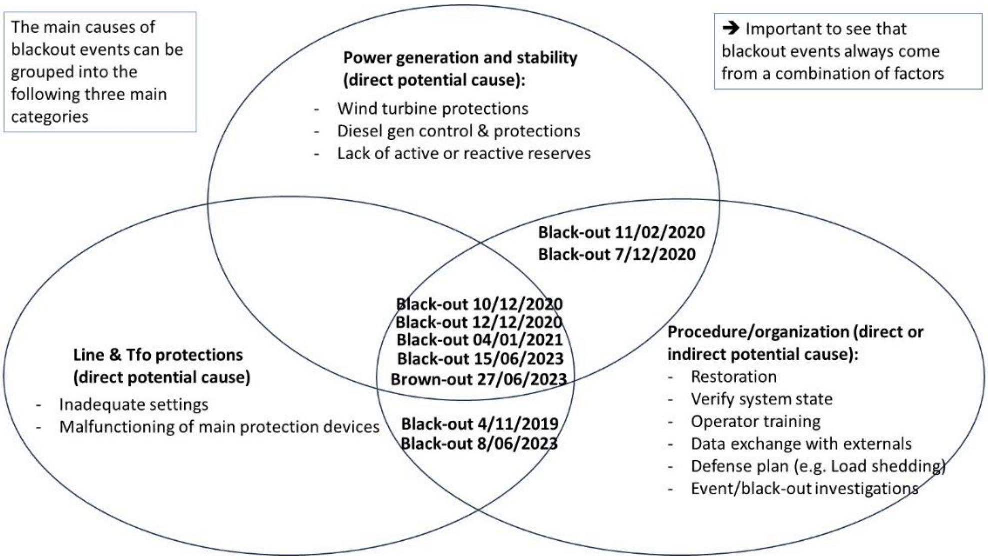
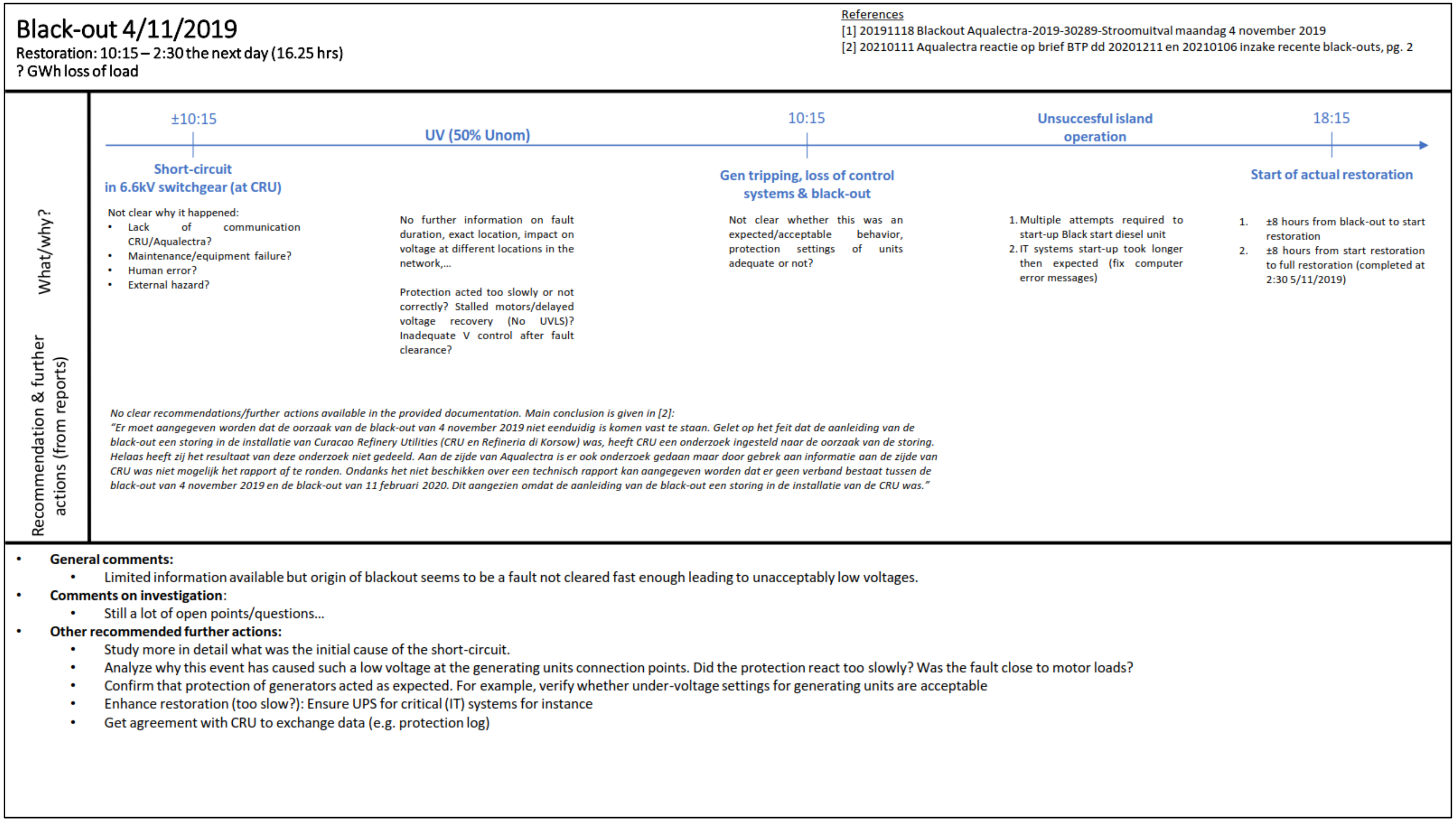


Figure 2: Main causes of blackout grouped by categories.



Black-out 4/11/2019

Restoration: 10:15 – 2:30 the next day (16.25 hrs)
? GWh loss of load

References
[1] 20191118 Blackout Aqualectra-2019-30289-Stroomuitval maandag 4 november 2019
[2] 20210111 Aqualectra reactie op brief BTP dd 20201211 en 20210106 inzake recente black-outs, pg. 2

Not clear why it happened:
- Lack of communication CRU/Aqualectra?
- Maintenance/equipment failure?
- Human error?
- External hazard?

No further information on fault duration, exact location, impact on voltage at different locations in the network,...

Protection acted too slowly or not correctly? Stalled motors/delayed voltage recovery (No UVLS)? Inadequate V control after fault clearance?

Not clear whether this was an expected/acceptable behavior, protection settings of units adequate or not?

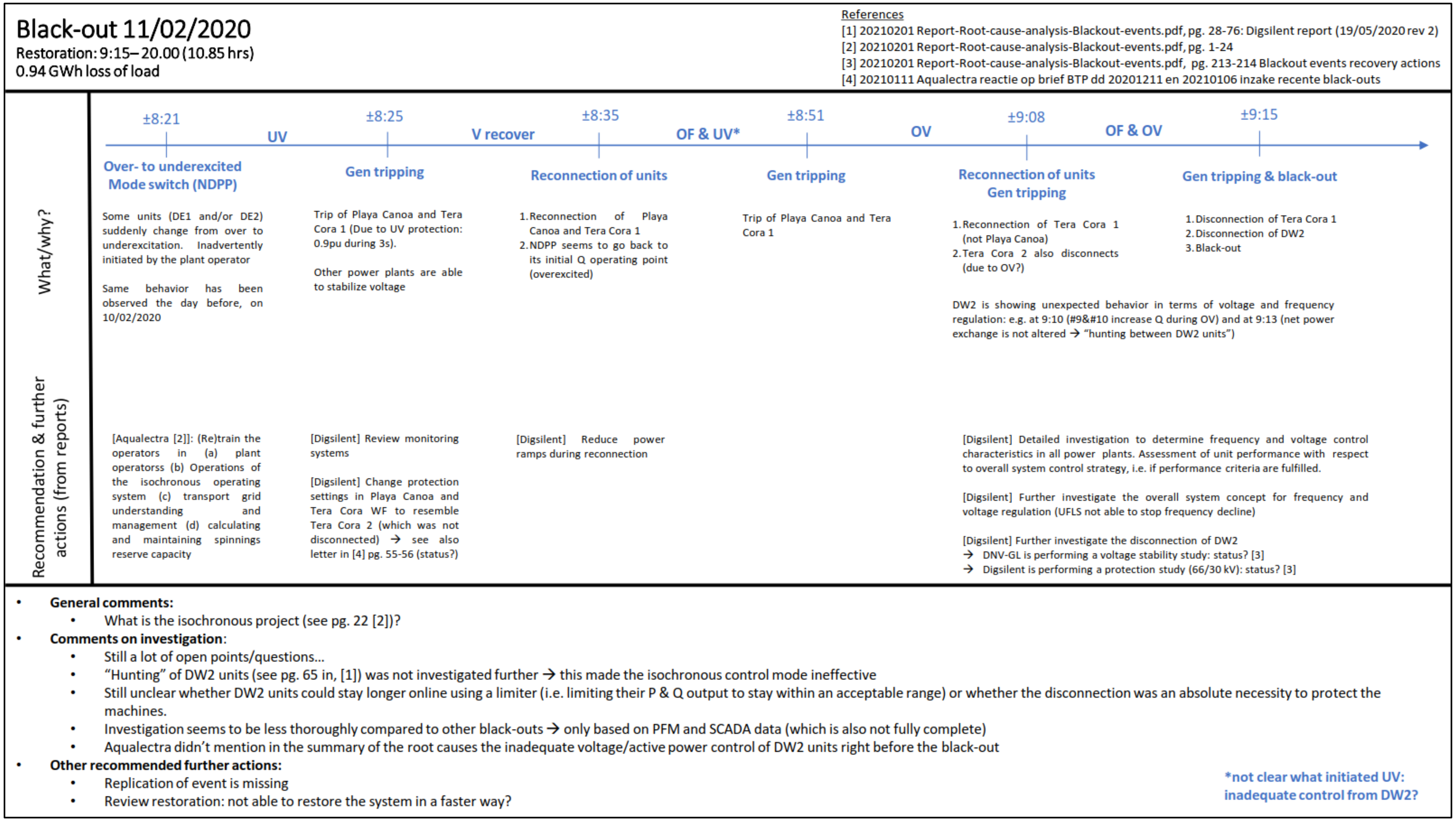
1. Multiple attempts required to start-up Black start diesel unit
2. IT systems start-up took longer then expected (fix computer error messages)

1. ±8 hours from black-out to start restoration
2. ±8 hours from start restoration to full restoration (completed at 2:30 5/11/2019)

No clear recommendations/further actions available in the provided documentation. Main conclusion is given in [2]:
"Er moet aangegeven worden dat de oorzaak van de black-out van 4 november 2019 niet eenduidig is komen vast te staan. Gelet op het feit dat de aanleiding van de black-out een storing in de installatie van Curacao Refinery Utilities (CRU en Refineria di Korsow) was, heeft CRU een onderzoek ingesteld naar de oorzaak van de storing. Helaas heeft zij het resultaat van deze onderzoek niet gedeeld. Aan de zijde van Aqualectra is er ook onderzoek gedaan maar door gebrek aan informatie aan de zijde van CRU was niet mogelijk het rapport af te ronden. Ondanks het niet beschikken over een technisch rapport kan aangegeven worden dat er geen verband bestaat tussen de black-out van 4 november 2019 en de black-out van 11 februari 2020. Dit aangezien omdat de aanleiding van de black-out een storing in de installatie van de CRU was."

- **General comments:**
  - Limited information available but origin of blackout seems to be a fault not cleared fast enough leading to unacceptably low voltages.
- **Comments on investigation**:
  - Still a lot of open points/questions...
- **Other recommended further actions:**
  - Study more in detail what was the initial cause of the short-circuit.
  - Analyze why this event has caused such a low voltage at the generating units connection points. Did the protection react too slowly? Was the fault close to motor loads?
  - Confirm that protection of generators acted as expected. For example, verify whether under-voltage settings for generating units are acceptable
  - Enhance restoration (too slow?): Ensure UPS for critical (IT) systems for instance
  - Get agreement with CRU to exchange data (e.g. protection log)

Figure 3: Overview blackout 4/11/2019



Black-out 11/02/2020

Restoration: 9:15– 20.00 (10.85 hrs)
0.94 GWh loss of load

References
[1] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg. 28-76: Digsilent report (19/05/2020 rev 2)
[2] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg. 1-24
[3] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg. 213-214 Blackout events recovery actions
[4] 20210111 Aqualectra reactie op brief BTP dd 20201211 en 20210106 inzake recente black-outs

What/why?

±8:21 — UV — ±8:25 — V recover — ±8:35 — OF & UV* — ±8:51 — OV — ±9:08 — OF & OV — ±9:15

±8:21 Over- to underexcited Mode switch (NDPP)

Some units (DE1 and/or DE2) suddenly change from over to underexcitation. Inadvertently initiated by the plant operator

Same behavior has been observed the day before, on 10/02/2020

±8:25 Gen tripping

Trip of Playa Canoa and Tera Cora 1 (Due to UV protection: 0.9pu during 3s).

Other power plants are able to stabilize voltage

±8:35 Reconnection of units

1. Reconnection of Playa Canoa and Tera Cora 1
2. NDPP seems to go back to its initial Q operating point (overexcited)

±8:51 Gen tripping

Trip of Playa Canoa and Tera Cora 1

±9:08 Reconnection of units Gen tripping

1. Reconnection of Tera Cora 1 (not Playa Canoa)
2. Tera Cora 2 also disconnects (due to OV?)

±9:15 Gen tripping & black-out

1. Disconnection of Tera Cora 1
2. Disconnection of DW2
3. Black-out

DW2 is showing unexpected behavior in terms of voltage and frequency regulation: e.g. at 9:10 (#9&#10 increase Q during OV) and at 9:13 (net power exchange is not altered → "hunting between DW2 units")

Recommendation & further actions (from reports)

[Aqualectra [2]]: (Re)train the operators in (a) plant operatorss (b) Operations of the isochronous operating system (c) transport grid understanding and management (d) calculating and maintaining spinnings reserve capacity

[Digsilent] Review monitoring systems

[Digsilent] Change protection settings in Playa Canoa and Tera Cora WF to resemble Tera Cora 2 (which was not disconnected) → see also letter in [4] pg. 55-56 (status?)

[Digsilent] Reduce power ramps during reconnection

[Digsilent] Detailed investigation to determine frequency and voltage control characteristics in all power plants. Assessment of unit performance with respect to overall system control strategy, i.e. if performance criteria are fulfilled.

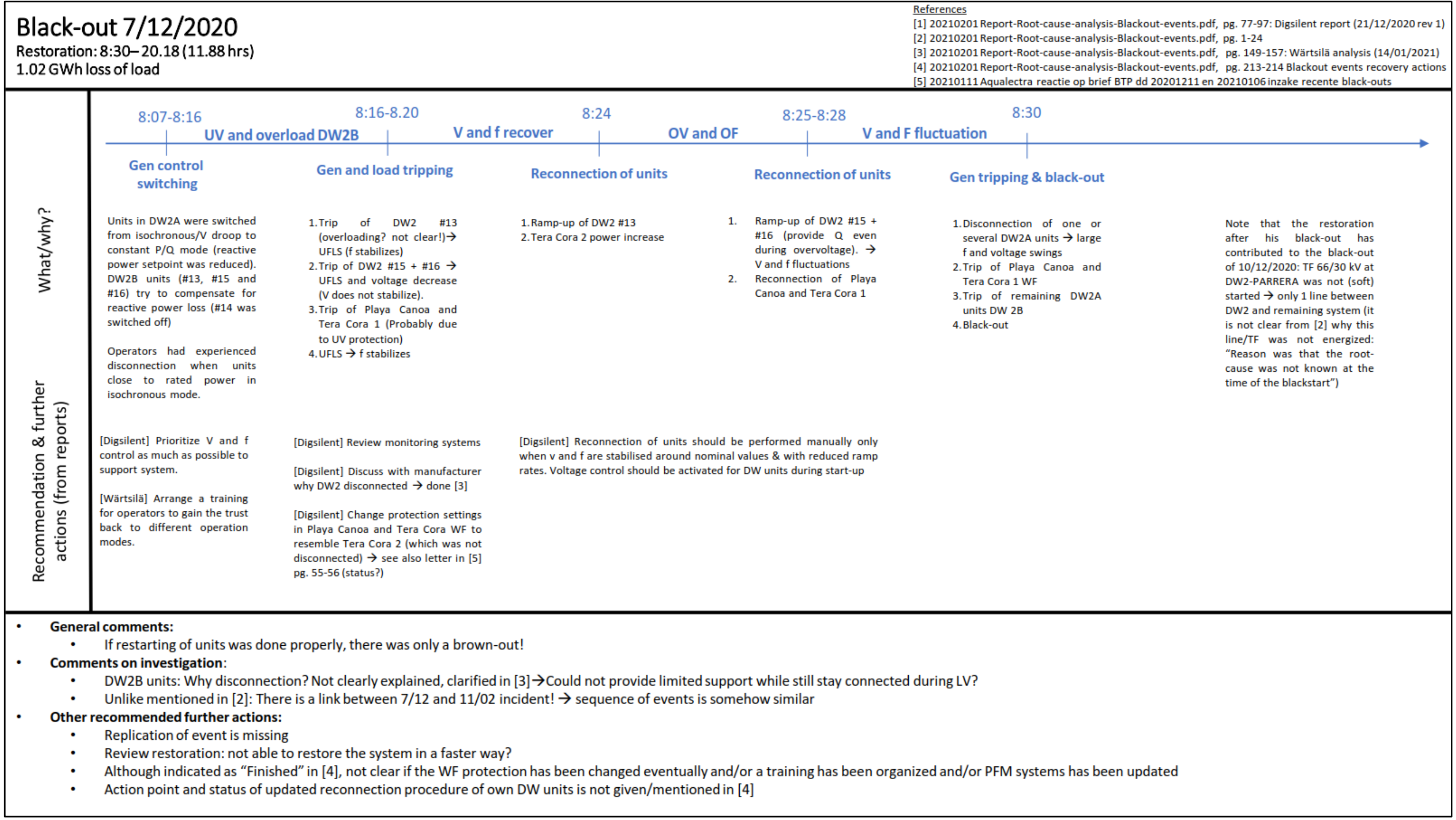
[Digsilent] Further investigate the overall system concept for frequency and voltage regulation (UFLS not able to stop frequency decline)

[Digsilent] Further investigate the disconnection of DW2
→ DNV-GL is performing a voltage stability study: status? [3]
→ Digsilent is performing a protection study (66/30 kV): status? [3]

- **General comments:**
  - What is the isochronous project (see pg. 22 [2])?
- **Comments on investigation**:
  - Still a lot of open points/questions…
  - "Hunting" of DW2 units (see pg. 65 in, [1]) was not investigated further → this made the isochronous control mode ineffective
  - Still unclear whether DW2 units could stay longer online using a limiter (i.e. limiting their P & Q output to stay within an acceptable range) or whether the disconnection was an absolute necessity to protect the machines.
  - Investigation seems to be less thoroughly compared to other black-outs → only based on PFM and SCADA data (which is also not fully complete)
  - Aqualectra didn't mention in the summary of the root causes the inadequate voltage/active power control of DW2 units right before the black-out
- **Other recommended further actions:**
  - Replication of event is missing
  - Review restoration: not able to restore the system in a faster way?

*not clear what initiated UV: inadequate control from DW2?

Figure 4: Overview blackout 11/02/2020



Black-out 7/12/2020

Restoration: 8:30– 20.18 (11.88 hrs)
1.02 GWh loss of load

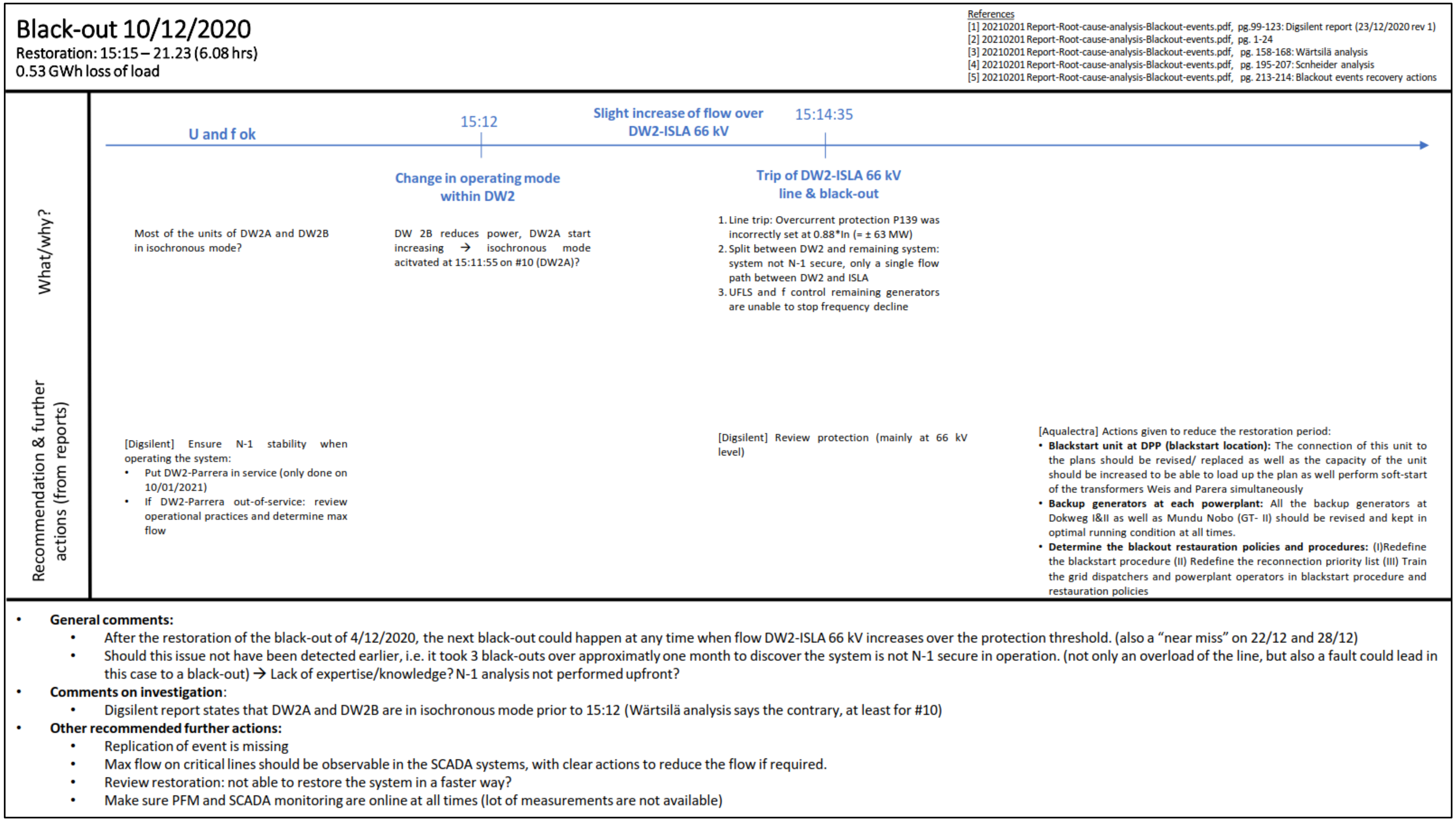
References
[1] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg. 77-97: Digsilent report (21/12/2020 rev 1)
[2] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg. 1-24
[3] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg. 149-157: Wärtsilä analysis (14/01/2021)
[4] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg. 213-214 Blackout events recovery actions
[5] 20210111 Aqualectra reactie op brief BTP dd 20201211 en 20210106 inzake recente black-outs

8:07-8:16 — UV and overload DW2B — 8:16-8.20 — V and f recover — 8:24 — OV and OF — 8:25-8:28 — V and F fluctuation — 8:30

	8:07-8:16	8:16-8.20	8:24	8:25-8:28	8:30	
	Gen control switching	**Gen and load tripping**	**Reconnection of units**	**Reconnection of units**	**Gen tripping & black-out**	
What/why?	Units in DW2A were switched from isochronous/V droop to constant P/Q mode (reactive power setpoint was reduced). DW2B units (#13, #15 and #16) try to compensate for reactive power loss (#14 was switched off) Operators had experienced disconnection when units close to rated power in isochronous mode.	1. Trip of DW2 #13 (overloading? not clear!)→ UFLS (f stabilizes) 2. Trip of DW2 #15 + #16 → UFLS and voltage decrease (V does not stabilize). 3. Trip of Playa Canoa and Tera Cora 1 (Probably due to UV protection) 4. UFLS → f stabilizes	1. Ramp-up of DW2 #13 2. Tera Cora 2 power increase	1. Ramp-up of DW2 #15 + #16 (provide Q even during overvoltage). → V and f fluctuations 2. Reconnection of Playa Canoa and Tera Cora 1	1. Disconnection of one or several DW2A units → large f and voltage swings 2. Trip of Playa Canoa and Tera Cora 1 WF 3. Trip of remaining DW2A units DW 2B 4. Black-out	Note that the restoration after his black-out has contributed to the black-out of 10/12/2020: TF 66/30 kV at DW2-PARRERA was not (soft) started → only 1 line between DW2 and remaining system (it is not clear from [2] why this line/TF was not energized: "Reason was that the root-cause was not known at the time of the blackstart")
Recommendation & further actions (from reports)	[Digsilent] Prioritize V and f control as much as possible to support system. [Wärtsilä] Arrange a training for operators to gain the trust back to different operation modes.	[Digsilent] Review monitoring systems [Digsilent] Discuss with manufacturer why DW2 disconnected → done [3] [Digsilent] Change protection settings in Playa Canoa and Tera Cora WF to resemble Tera Cora 2 (which was not disconnected) → see also letter in [5] pg. 55-56 (status?)	[Digsilent] Reconnection of units should be performed manually only when v and f are stabilised around nominal values & with reduced ramp rates. Voltage control should be activated for DW units during start-up			

- **General comments:**
  - If restarting of units was done properly, there was only a brown-out!
- **Comments on investigation**:
  - DW2B units: Why disconnection? Not clearly explained, clarified in [3]→Could not provide limited support while still stay connected during LV?
  - Unlike mentioned in [2]: There is a link between 7/12 and 11/02 incident! → sequence of events is somehow similar
- **Other recommended further actions:**
  - Replication of event is missing
  - Review restoration: not able to restore the system in a faster way?
  - Although indicated as "Finished" in [4], not clear if the WF protection has been changed eventually and/or a training has been organized and/or PFM systems has been updated
  - Action point and status of updated reconnection procedure of own DW units is not given/mentioned in [4]

Figure 5: Overview blackout 7/12/2020



Black-out 10/12/2020

Restoration: 15:15 – 21.23 (6.08 hrs)
0.53 GWh loss of load

References
[1] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg.99-123: Digsilent report (23/12/2020 rev 1)
[2] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg. 1-24
[3] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg. 158-168: Wärtsilä analysis
[4] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg. 195-207: Scnheider analysis
[5] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg. 213-214: Blackout events recovery actions

Most of the units of DW2A and DW2B in isochronous mode?

DW 2B reduces power, DW2A start increasing → isochronous mode acitvated at 15:11:55 on #10 (DW2A)?

1. Line trip: Overcurrent protection P139 was incorrectly set at 0.88*In (= ± 63 MW)
2. Split between DW2 and remaining system: system not N-1 secure, only a single flow path between DW2 and ISLA
3. UFLS and f control remaining generators are unable to stop frequency decline

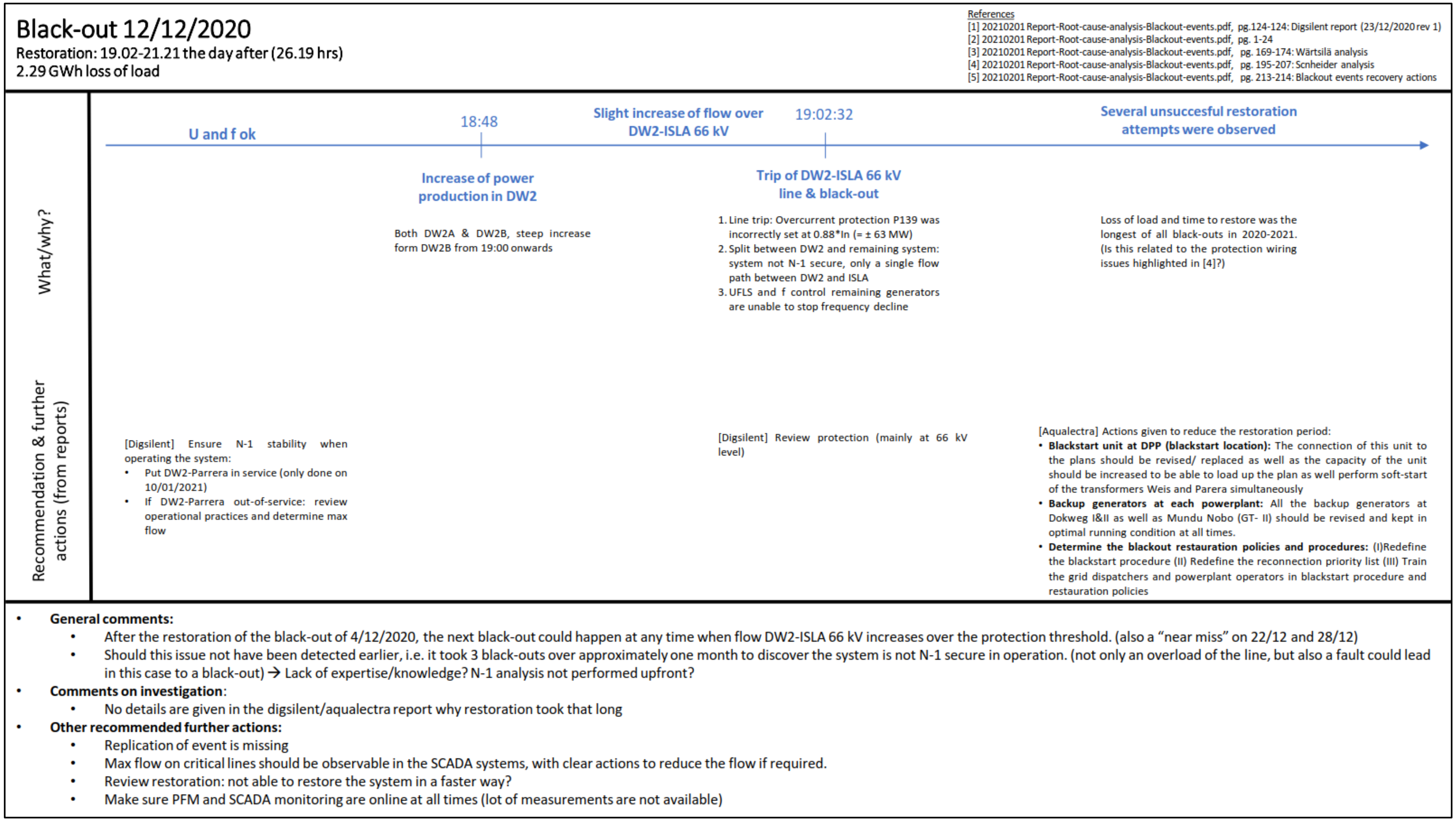
[Digsilent] Ensure N-1 stability when operating the system:
- Put DW2-Parrera in service (only done on 10/01/2021)
- If DW2-Parrera out-of-service: review operational practices and determine max flow

[Digsilent] Review protection (mainly at 66 kV level)

[Aqualectra] Actions given to reduce the restoration period:
- **Blackstart unit at DPP (blackstart location):** The connection of this unit to the plans should be revised/ replaced as well as the capacity of the unit should be increased to be able to load up the plan as well perform soft-start of the transformers Weis and Parera simultaneously
- **Backup generators at each powerplant:** All the backup generators at Dokweg I&II as well as Mundu Nobo (GT- II) should be revised and kept in optimal running condition at all times.
- **Determine the blackout restauration policies and procedures:** (I)Redefine the blackstart procedure (II) Redefine the reconnection priority list (III) Train the grid dispatchers and powerplant operators in blackstart procedure and restauration policies

- **General comments:**
  - After the restoration of the black-out of 4/12/2020, the next black-out could happen at any time when flow DW2-ISLA 66 kV increases over the protection threshold. (also a “near miss” on 22/12 and 28/12)
  - Should this issue not have been detected earlier, i.e. it took 3 black-outs over approximatly one month to discover the system is not N-1 secure in operation. (not only an overload of the line, but also a fault could lead in this case to a black-out) → Lack of expertise/knowledge? N-1 analysis not performed upfront?
- **Comments on investigation**:
  - Digsilent report states that DW2A and DW2B are in isochronous mode prior to 15:12 (Wärtsilä analysis says the contrary, at least for #10)
- **Other recommended further actions:**
  - Replication of event is missing
  - Max flow on critical lines should be observable in the SCADA systems, with clear actions to reduce the flow if required.
  - Review restoration: not able to restore the system in a faster way?
  - Make sure PFM and SCADA monitoring are online at all times (lot of measurements are not available)

Figure 6: Overview blackout 10/12/2020



Black-out 12/12/2020

Restoration: 19.02-21.21 the day after (26.19 hrs)
2.29 GWh loss of load

References
[1] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg.124-124: Digsilent report (23/12/2020 rev 1)
[2] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg. 1-24
[3] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg. 169-174: Wärtsilä analysis
[4] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg. 195-207: Scnheider analysis
[5] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg. 213-214: Blackout events recovery actions

What/why?

U and f ok

18:48

Increase of power production in DW2

Both DW2A & DW2B, steep increase form DW2B from 19:00 onwards

Slight increase of flow over DW2-ISLA 66 kV

19:02:32

Trip of DW2-ISLA 66 kV line & black-out

1. Line trip: Overcurrent protection P139 was incorrectly set at 0.88*In (= ± 63 MW)
2. Split between DW2 and remaining system: system not N-1 secure, only a single flow path between DW2 and ISLA
3. UFLS and f control remaining generators are unable to stop frequency decline

Several unsuccesful restoration attempts were observed

Loss of load and time to restore was the longest of all black-outs in 2020-2021. (Is this related to the protection wiring issues highlighted in [4]?)

Recommendation & further actions (from reports)

[Digsilent] Ensure N-1 stability when operating the system:

- Put DW2-Parrera in service (only done on 10/01/2021)
- If DW2-Parrera out-of-service: review operational practices and determine max flow

[Digsilent] Review protection (mainly at 66 kV level)

[Aqualectra] Actions given to reduce the restoration period:

- **Blackstart unit at DPP (blackstart location):** The connection of this unit to the plans should be revised/ replaced as well as the capacity of the unit should be increased to be able to load up the plan as well perform soft-start of the transformers Weis and Parera simultaneously
- **Backup generators at each powerplant:** All the backup generators at Dokweg I&II as well as Mundu Nobo (GT- II) should be revised and kept in optimal running condition at all times.
- **Determine the blackout restauration policies and procedures:** (I)Redefine the blackstart procedure (II) Redefine the reconnection priority list (III) Train the grid dispatchers and powerplant operators in blackstart procedure and restauration policies

- **General comments:**
  - After the restoration of the black-out of 4/12/2020, the next black-out could happen at any time when flow DW2-ISLA 66 kV increases over the protection threshold. (also a “near miss” on 22/12 and 28/12)
  - Should this issue not have been detected earlier, i.e. it took 3 black-outs over approximately one month to discover the system is not N-1 secure in operation. (not only an overload of the line, but also a fault could lead in this case to a black-out) → Lack of expertise/knowledge? N-1 analysis not performed upfront?
- **Comments on investigation**:
  - No details are given in the digsilent/aqualectra report why restoration took that long
- **Other recommended further actions:**
  - Replication of event is missing
  - Max flow on critical lines should be observable in the SCADA systems, with clear actions to reduce the flow if required.
  - Review restoration: not able to restore the system in a faster way?
  - Make sure PFM and SCADA monitoring are online at all times (lot of measurements are not available)

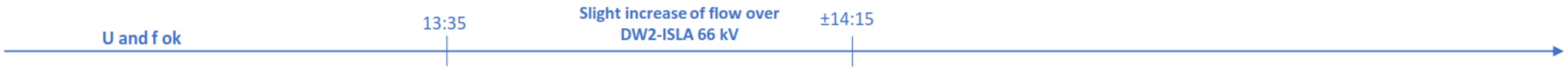
Figure 7: Overview blackout 12/12/2020

Black-out 04/01/2021

Restoration: 14:15-19:02 (4.85 hrs)
0.453 GWh loss of load

References
[1] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg. 1-24
[2] P2029_Aqualectra_Event-Analysis-20210104_REPTRIP04_R01_V01.pdf (available on aqualectra website)
[3] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg. 174-180: Wärtsilä analysis
[4] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg. 195-207: Scnheider analysis
[5] 20210201 Report-Root-cause-analysis-Blackout-events.pdf, pg. 213-214: Blackout events recovery actions

What/why?



Increase of power production in DW2

Both DW2A & DW2B, steep increase of DW2B from 19:00 onwards

Trip of DW2-ISLA 66 kV line & black-out

1. Line trip: Overcurrent protection P139 was incorrectly set at 0.88*In (= ± 63 MW)
2. Split between DW2 and remaining system: system not N-1 secure, only a single flow path between DW2 and ISLA
3. UFLS and f control remaining generators are unable to sop frequency decline

Recommendation & further actions (from reports)

[Digsilent] Ensure N-1 stability when operating the system:

- Put DW2-Parrera in service (only done on 10/01/2021)
- If DW2-Parrera out-of-service: review operational practices and determine max flow

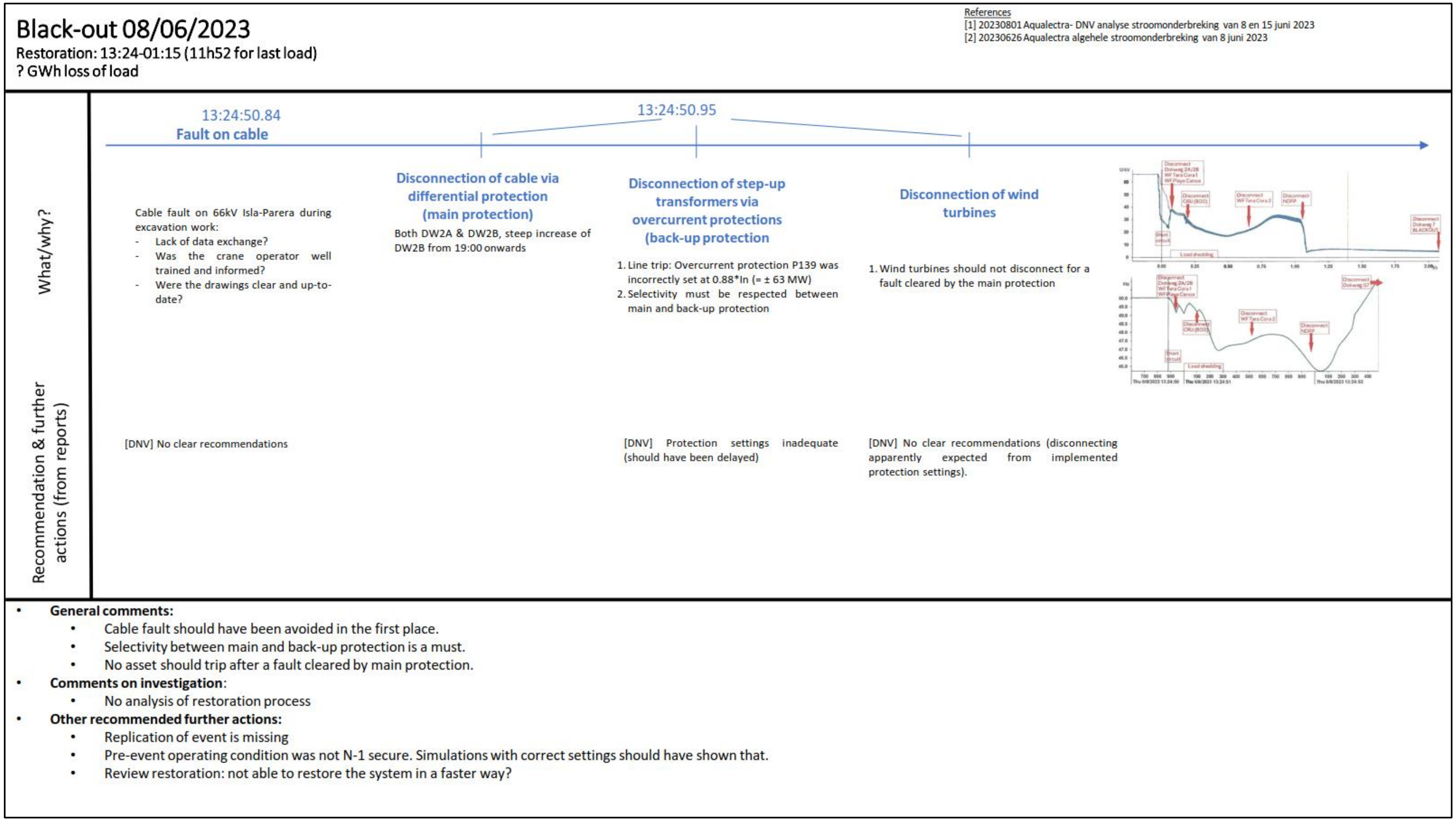
[Digsilent] Review protection (mainly at 66 kV level)

[Aqualectra] Actions given to reduce the restoration period:

- **Blackstart unit at DPP (blackstart location):** The connection of this unit to the plans should be revised/ replaced as well as the capacity of the unit should be increased to be able to load up the plan as well perform soft-start of the transformers Weis and Parera simultaneously
- **Backup generators at each powerplant:** All the backup generators at Dokweg I&II as well as Mundu Nobo (GT- II) should be revised and kept in optimal running condition at all times.
- **Determine the blackout restauration policies and procedures:** (I)Redefine the blackstart procedure (II) Redefine the reconnection priority list (III) Train the grid dispatchers and powerplant operators in blackstart procedure and restauration policies

- **General comments:**
  - After the restoration of the black-out of 4/12/2020, the next black-out could happen at any time when flow DW2-ISLA 66 kV increases over the protection threshold. (also a “near miss” on 22/12 and 28/12)
  - Should this issue not have been detected earlier, i.e. it took 3 black-outs over approximately one month to discover the system is not N-1 secure in operation. (not only an overload of the line, but also a fault could lead in this case to a black-out) → Lack of expertise/knowledge? N-1 analysis not performed upfront?
- **Comments on investigation**:
  - Similar cause than December events but root cause was not clearly identified → from [4], another protection device that the one causing the blackout was turned off... It is recommended to perform invesigations as soon as possible after a blackout !
- **Other recommended further actions:**
  - Replication of event is missing
  - Review restoration: not able to restore the system in a faster way?
  - Max flow on critical lines should be observable in the SCADA systems, with clear actions to reduce the flow if required.
  - Make sure PFM and SCADA monitoring are online at all times (lot of measurements are not available)

Figure 8: Overview blackout 04/01/2021



Black-out 08/06/2023

Restoration: 13:24-01:15 (11h52 for last load)
? GWh loss of load

References
[1] 20230801 Aqualectra- DNV analyse stroomonderbreking van 8 en 15 juni 2023
[2] 20230626 Aqualectra algehele stroomonderbreking van 8 juni 2023

What/why?

13:24:50.84
Fault on cable

Cable fault on 66kV Isla-Parera during excavation work:
- Lack of data exchange?
- Was the crane operator well trained and informed?
- Were the drawings clear and up-to-date?

13:24:50.95

Disconnection of cable via differential protection (main protection)

Both DW2A & DW2B, steep increase of DW2B from 19:00 onwards

Disconnection of step-up transformers via overcurrent protections (back-up protection

1. Line trip: Overcurrent protection P139 was incorrectly set at 0.88*In (= ± 63 MW)
2. Selectivity must be respected between main and back-up protection

Disconnection of wind turbines

1. Wind turbines should not disconnect for a fault cleared by the main protection

Recommendation & further actions (from reports)

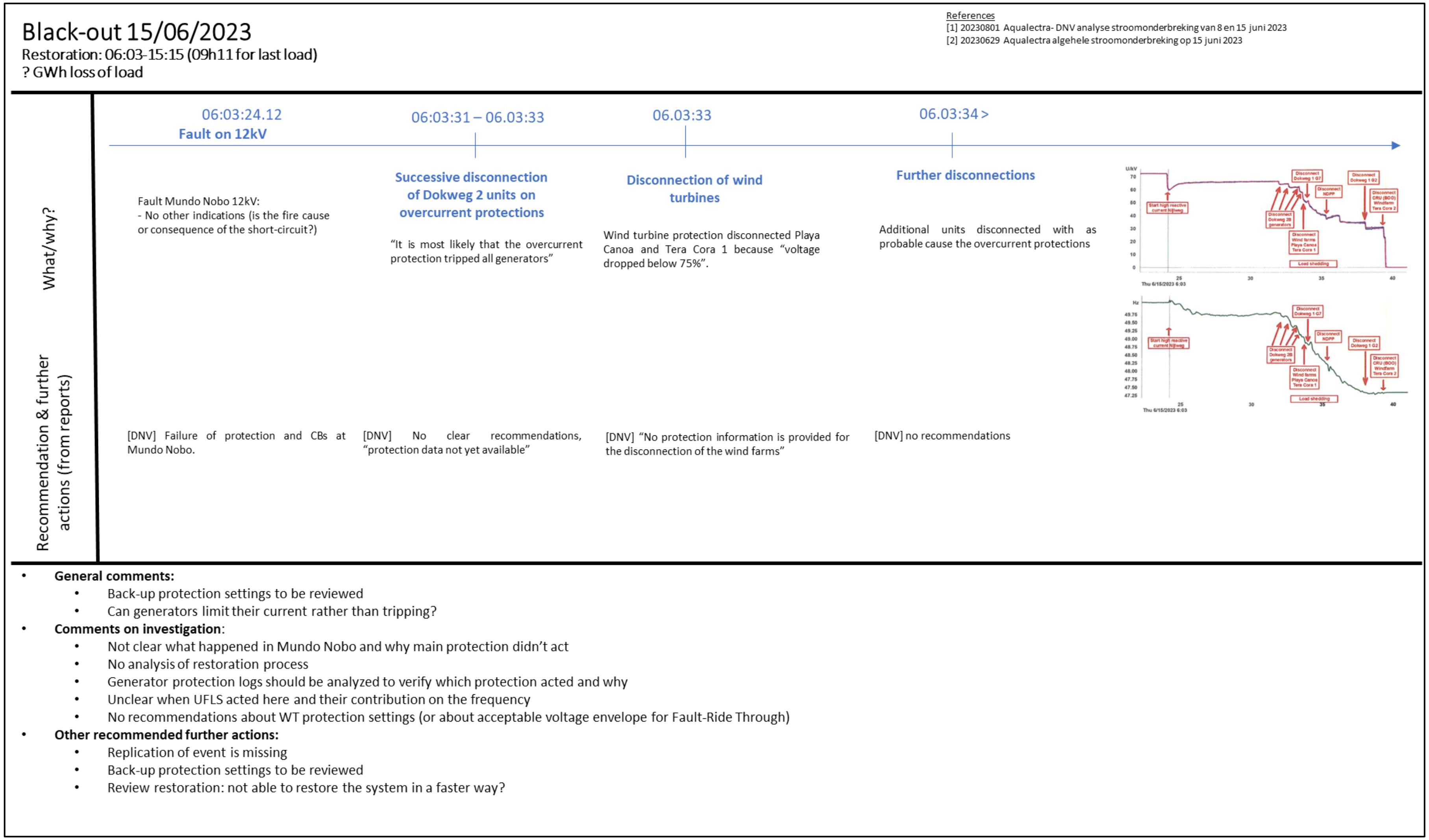
[DNV] No clear recommendations

[DNV] Protection settings inadequate (should have been delayed)

[DNV] No clear recommendations (disconnecting apparently expected from implemented protection settings).

- **General comments:**
  - Cable fault should have been avoided in the first place.
  - Selectivity between main and back-up protection is a must.
  - No asset should trip after a fault cleared by main protection.
- **Comments on investigation**:
  - No analysis of restoration process
- **Other recommended further actions:**
  - Replication of event is missing
  - Pre-event operating condition was not N-1 secure. Simulations with correct settings should have shown that.
  - Review restoration: not able to restore the system in a faster way?

Figure 9: Overview blackout 08/06/2023



Black-out 15/06/2023

Restoration: 06:03-15:15 (09h11 for last load)
? GWh loss of load

References
[1] 20230801 Aqualectra- DNV analyse stroomonderbreking van 8 en 15 juni 2023
[2] 20230629 Aqualectra algehele stroomonderbreking op 15 juni 2023

What/why?

Recommendation & further actions (from reports)

06:03:24.12
Fault on 12kV

Fault Mundo Nobo 12kV:
- No other indications (is the fire cause or consequence of the short-circuit?)

[DNV] Failure of protection and CBs at Mundo Nobo.

06:03:31 – 06.03:33
Successive disconnection of Dokweg 2 units on overcurrent protections

"It is most likely that the overcurrent protection tripped all generators"

[DNV] No clear recommendations, "protection data not yet available"

06.03:33
Disconnection of wind turbines

Wind turbine protection disconnected Playa Canoa and Tera Cora 1 because "voltage dropped below 75%".

[DNV] "No protection information is provided for the disconnection of the wind farms"

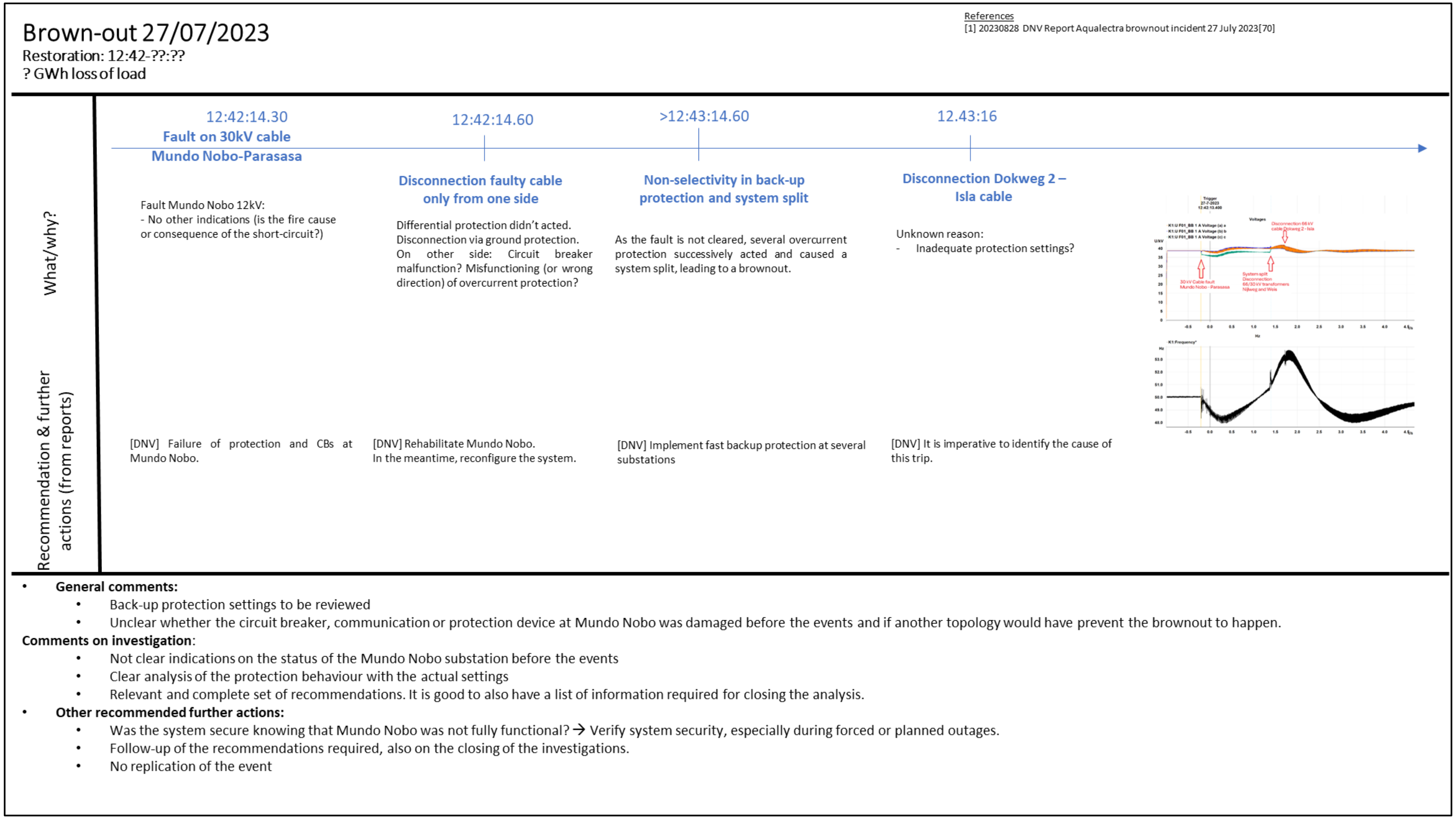
06.03:34 >
Further disconnections

Additional units disconnected with as probable cause the overcurrent protections

[DNV] no recommendations

- **General comments:**
  - Back-up protection settings to be reviewed
  - Can generators limit their current rather than tripping?
- **Comments on investigation**:
  - Not clear what happened in Mundo Nobo and why main protection didn't act
  - No analysis of restoration process
  - Generator protection logs should be analyzed to verify which protection acted and why
  - Unclear when UFLS acted here and their contribution on the frequency
  - No recommendations about WT protection settings (or about acceptable voltage envelope for Fault-Ride Through)
- **Other recommended further actions:**
  - Replication of event is missing
  - Back-up protection settings to be reviewed
  - Review restoration: not able to restore the system in a faster way?

Figure 10: Overview blackout 15/06/2023



Brown-out 27/07/2023

Restoration: 12:42-??:??
? GWh loss of load

References
[1] 20230828 DNV Report Aqualectra brownout incident 27 July 2023[70]

What/why?

12:42:14.30
Fault on 30kV cable Mundo Nobo-Parasasa

Fault Mundo Nobo 12kV:
- No other indications (is the fire cause or consequence of the short-circuit?)

12:42:14.60
Disconnection faulty cable only from one side

Differential protection didn't acted. Disconnection via ground protection. On other side: Circuit breaker malfunction? Misfunctioning (or wrong direction) of overcurrent protection?

>12:43:14.60
Non-selectivity in back-up protection and system split

As the fault is not cleared, several overcurrent protection successively acted and caused a system split, leading to a brownout.

12.43:16
Disconnection Dokweg 2 – Isla cable

Unknown reason:
- Inadequate protection settings?

Recommendation & further actions (from reports)

[DNV] Failure of protection and CBs at Mundo Nobo.

[DNV] Rehabilitate Mundo Nobo.
In the meantime, reconfigure the system.

[DNV] Implement fast backup protection at several substations

[DNV] It is imperative to identify the cause of this trip.

- **General comments:**
  - Back-up protection settings to be reviewed
  - Unclear whether the circuit breaker, communication or protection device at Mundo Nobo was damaged before the events and if another topology would have prevent the brownout to happen.

Comments on investigation:
  - Not clear indications on the status of the Mundo Nobo substation before the events
  - Clear analysis of the protection behaviour with the actual settings
  - Relevant and complete set of recommendations. It is good to also have a list of information required for closing the analysis.
- **Other recommended further actions:**
  - Was the system secure knowing that Mundo Nobo was not fully functional? → Verify system security, especially during forced or planned outages.
  - Follow-up of the recommendations required, also on the closing of the investigations.
  - No replication of the event

Figure 11: Overview brown-out 27/07/2023

3. Task 1: Focus on protection

3.1. Best practices on protection principles

3.1.1. Principles of differential protections

Differential protection relays are suited to protect a well-defined protection zone. They are comparing currents at both ends of the protected elements. However, this type of relay will not act for faults external to the protection zone. For this reason, differential protections usually act as fast as possible when detecting a fault because there is no selectivity issue with this type of protection. But consequently differential protection do not offer back-up protection in case of malfunction of a downstream element. Back-up protections, acting more slowly, should be foreseen. These back-up protection will act in case of malfunctioning of the differential relay (with higher time delay).

3.1.2. Principles of overcurrent protections

Overcurrent protection relays may have different characteristics and thresholds. Usually 2 thresholds can be set, one for detecting currents too high for the characteristics of the protected elements (overload) and one for short-circuit currents. When working with overcurrent protection, selectivity is a crucial aspect and coordination between different stages should be considered carefully. Usually, the selectivity is guaranteed by programing a difference in time delays between 2 protections (upstream relay should have a higher time delay compared to the downstream relay of at least 200 ms). Precise short-circuit current calculations can also be made in order to set the high threshold to an appropriate setting to avoid tripping for a short-circuit downstream the next protection relays (in this case, shorter time may be used).

3.1.3. Protection coordination philosophy

Without entering too much in details of the protection aspects, the two following main principles can be followed:

- Selectivity must be guaranteed between main and back-up protections.
- In case of malfunctioning of the main protection, back-up protections must contain the fault while being as selective as possible.

It is therefore not an obligation of the back-up protections to be fully selective, but they have to make sure the fault will be cleared without causing a cascading event. Having a clear back-up philosophy would facilitate the tuning of protection parameters. For example, an option is to define some protection zones in the network and to tune the back-up protections to isolate a small zone of the network in case of a fault. This philosophy will use different protection parameters than a fully selective philosophy.

In a meshed network, directional overcurrent will be needed to discriminate if the faut is upwards or downwards the protection, it is not possible just by setting time delays.

3.2. Analysis of received documents

3.2.1. Analysis of investigations reports

3.2.1.1. Generator protections

On some blackouts (e.g. 4/11/2019, 15/06/2023), generators tripped on overcurrent. It is important to know the settings of these overcurrent protections and evaluate whether units could have stayed longer online. This should be further discussed with the manufacturer.

In a more general way, it must be verified in a selectivity study whether the generator overcurrent protections are adequately tuned with respect to the grid protections. The goal is indeed that the grid protections isolate the fault and acts before action of the overcurrent protection of the generating units.

On 7/12/2020 blackout, the exact reason for the tripping of Dokweg units is not fully clear. It is important to emphasize that Dokweg units are key for the stability of the system and should stay online as long as possible without risking damage. Therefore, the exact reason of tripping of these units should be known.

3.2.1.2. Main vs back-up protections

Main protections do not operate in some situations. It is not clear what is the cause of the malfunctioning of the main protections and it should therefore be clarified.

Regarding the selectivity principle, we can identify the three following cases:

- During the blackout of the 8 June 2023, there is no selectivity between main and back-up protections. This is against protection selectivity principles.
- During two blackouts (4/11/2019 and 15/06/2023) and the brownout (27/07/2023), full selectivity on grid protection was not achieved by the back-up protections.
- During two blackouts (4/11/2019, 15/06/2023), selectivity was not achieved between back-up grid protection and overcurrent generating unit protections.

From what we could observe, the back-up protection goal (which is to contain the fault before cascading events such as the activation of the overcurrent protections of the generating units) was not met and led to blackout situations. This is a concern for the stability of the system and selectivity between grid protections and generator protections must be reviewed.

3.2.2. Analysis of other received documents

3.2.2.1. Protection Direction

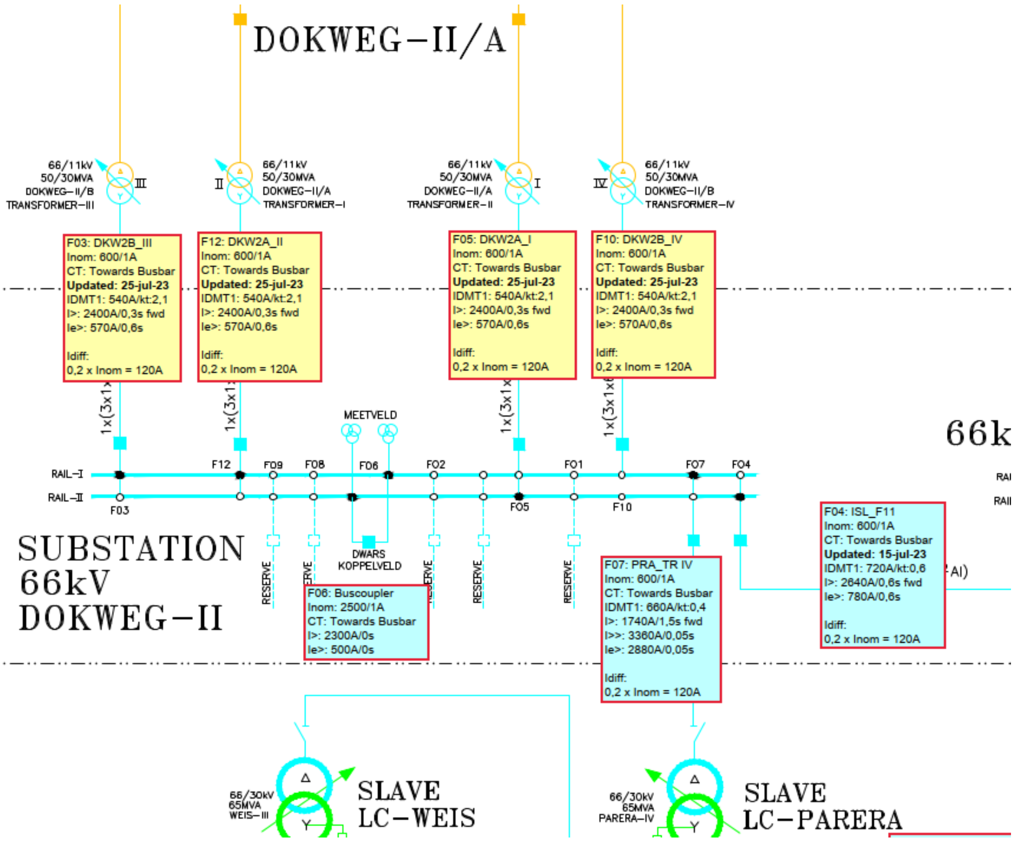


Figure 12: Extract of SLD provided with protection settings

A SLD with actual protection settings has been provided by Aqualectra. This is a good and complete document. However, it seems that this is provided with significant manual work, which is prone to mistake. Also, even if the author of the document wrote an updated date, this type of document makes difficult to track the historical changes in the protection settings. Another comment is that the direction indicates the direction of the CT. However, the direction of the protection also depends on the relay programming and is thus not clearly indicated on the SLD.

In summary, the document seems to confirm that there is a manual management of the protection database which is not recommended. There are existing commercial tools able to store properly any changes and communicate with protection devices, and also be used for performing simulations.

3.2.2.2. Minimum short-circuit current

Maximum and minimum short circuit currents have been provided[2]. To our surprise, the minimum short-circuit current was calculated on the same dispatch as the maximum short-circuit current (i.e. with many machines online).

It must be emphasized that minimum short-circuit current should be calculated based on a minimum number of units online as this will provide lower short-circuit current. This

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[2] *"Transmission System min. short circuit.pdf"*

observation is in line with the document “Review Protection Coordination study of Aqualectra (DNV)”, in which the following is said “*The short-circuit currents are based on standard IEC60909, a more accurate calculation method (“Complete”) should be used to check the sensitivity of protection systems during minimum short-circuit currents”*.

This is an important remark because short-circuit current with few generating units connected might potentially be below the over-current protection threshold.

3.3. List of actions listed in the reports regarding protections and follow-up

This section summarizes the most relevant actions that were listed in the document provided. From these documents, the status of these recommended actions was not always clearly indicated. Aqualectra provided clarification when reviewing the draft version of this report. This clarification is included in the status column.

Action	Report	Status[3]	Comment
Adaption of overcurrent protection settings (Quick win)	Beveilingsconcept aanpassingen_Quick_wins_20230807 & Review Protection Coordination study of Aqualectra (DNV)	*“Aqualectra confims that the settings are implemented according to DNV advice.”*	Ongoing action with DNV (probably some already implemented, to be confirmed by Aqualectra)
Implement fast back-up protection at Nijlweg, on both Mundo Nobo circuits	DNV report 27 July	*“Aqualectra decommissioned the COQ switchgear that wasn't working properly; now only the Fuji (metal-clad) switchgear is in service. “*	Exact state of Mundo Nobo not clear from the report. It seems that some devices are not functioning properly but to be confirm by Aqualectra.
Rehabilitate (or decommission) + Mundo Nobo	DNV report 27 July and DNV report 8 and 15 June	*“Aqualectra decommissioned the COQ switchgear that wasn't working properly; now only the Fuji (metal-clad) switchgear is in service. “*	
Protection scheme 66kV and 30kV shall be reviewed (including generator protection)	DNV report 8 and 15 June	*“This is ongoing and should be finished by the end of February 2024.”*	Probably ongoing study from DNV (to be confirm by Aqualectra)

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[3] *As communicated by Aqualectra in the document “Comments on Laborelec reports.pdf”*

Action	Report	Status[3]	Comment
(Back-up) protection at Mundo Nobo shall be reviewed	DNV report 8 and 15 June	*“This was done during the grid stability study realized by Digsilent.”*	Action linked to what happened during the brown-out. Aqualectra to confirm the status of this.
Establish fault protection philosophy	DNV report 8 and 15 June	*“DNV held a workshop with Aqualectra on protection philosophy for the 66 kV and 30 kV systems. The philosophy report is finalized. The protection settings study is ongoing, and implementation of new/adapted settings in the field will be prepared next.”*	Our understanding is that there is an ongoing study. Aqualectra to confirm.
Repair busbar protection Dokweg 2 and put this in service	Review Protection Coordination study of Aqualectra (DNV)	*“This is ongoing and should be finished by the end of February 2024.“*	
Short term plan, 30kV protection plan	Review Protection Coordination study of Aqualectra (DNV)	*“This is ongoing and should be finished by the end of February 2024.”*	
Mid-term plan 66kV protection plan	Review Protection Coordination study of Aqualectra (DNV)	*“This is ongoing and should be finished by the end of February 2024.”*	
Long-term plan	Review Protection Coordination study of Aqualectra (DNV)	*“This is ongoing and should be finished by the end of February 2024.”*	
Perform 66/30kV protection system study	Blackout event recovery actions table in “20210201 Report-Root-cause_analysis-Blackout-events”	*“This is ongoing and should be finished by the end of February 2024.”*	Our understanding is that there is an ongoing study. Aqualectra to confirm.
Generator disconnection (e.g. 11/02/2021)	Blackout event recovery actions table in “20210201 Report-Root-cause_analysis-Blackout-events”	*“This was done during the grid stability study realized by Digsilent.”*	“Further investigations to dermine the root cause of the disconnection”

Action	Report	Status[3]	Comment
After the addition of Dokweg-IIB substation, […] it is recommended that a protection study is conducted in order to analyze all the new scenarios that are possible given that the 66kV substation now has 4 incoming transformers instead of 2 as it was when the project was delivered so that the protection settings on the MiCOM relays can be adjusted.	Schneider report	*"This will be covered by the protection study."*	Please confirm date of last protection study.

Table 1: Summary of actions (from analyzed reports) related to protections

3.4. Our main recommendations regarding protections

The use of differential protection as main protection and overcurrent protection as back-up seems a reasonable choice. Other protection logic such as distance protections do not work well with short cables and therefore, the types of protection used are considered as adequate.

1. The way the protection settings are calculated for overcurrent protection is reasonable as it use minimum short-circuit current. However, selectivity studies should be updated regularly (typically every year) and **the minimum short-circuit current calculation should consider all representative operating conditions**. In particular, this current depends on the topology and number of online rotating units. In a system with high penetration of renewable energy, there are most likely some operating conditions with limited online machines and these points need therefore to be considered to verify the protection settings.

2. Also, **transformers and generators protections should be included in the selectivity study**. It is indeed important to ensure selectivity between cable, transformers and generators overcurrent protections.

3. In the investigation reports, it is not always clear which protection settings are implemented. This is not good practice. **Protection settings should be stored in a database, with date of last change**. And ideally should be used for simulation purposes in several operating conditions.

4. Task 2: Focus on power generation and system stability

4.1. Best practices on power system stability

4.1.1. Voltage and frequency stability

According to the IEEE/CIGRE joint task force, power system stability is defined as “the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.” This stability can be applied to a part of the interconnected system or the system as a whole. A further classification is generally made between the electrical parameter of interest, namely rotor angle stability, frequency stability and voltage stability[4], see Figure 13. Looking at the blackout investigations, the main challenges of the system of Curaçao are related to voltage and frequency stability.

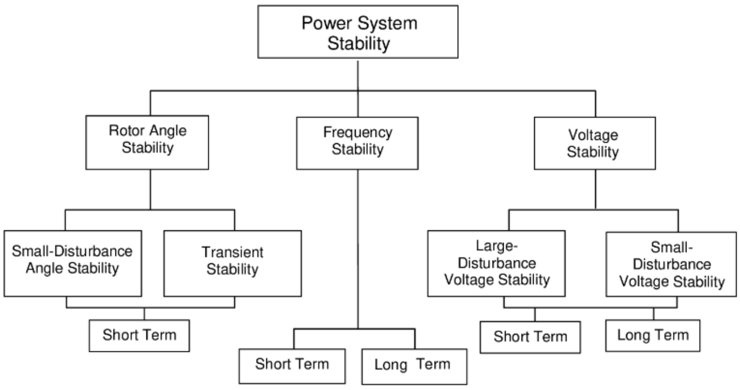

Figure 13 - Classification of power system stability

Voltage stability is characterized as being capable of maintaining, in N-0 situation, the voltage level at any node within the normal (contracted or agreed) voltage ranges. In N-1 situation, the voltage can deviate temporarily to exceptional ranges under the condition of the existence of remedial actions to go back to the normal voltage range. The system operator is responsible for maintaining voltage stability by controlling (and adequately planning for) the capability of the reactive power of the different generation units, the taps of transformer tap changers, the network topology, the available reactive power compensation equipment, etc. According to the Policy 3 of the operational handbook of ENTSO-E[5], a further split-up can be made regarding the reactive power resources:

- Rapid reactive power resources and reserves: System operators are committed to have available a sufficient reserve of rapid reactive power resources participating to the primary voltage control in order (i) to ensure normal operational conditions with a continuous evolving of load and transits and (ii) to prevent voltage collapse

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[4] *A revisited & extended classification is made by IEEE in 2020 including also converter driven stability and resonance stability*

[5] *ENTSO-E, the European Network of Transmission System Operators has published a handbook including policies for generation control, reserves, security criteria, emergency procedures and special operational measures. https://www.entsoe.eu/publications/system-operations-reports/*

after any contingency of the contingencies (including contingencies of one large reactive power source: compensation installation or generation unit).

- Other reactive power generation/absorption resources: System operators have to keep available a sufficient number of other reactive power sources like generators, capacitors and reactors connected to the grid, which contribute to reactive power generation or absorption, in order to maintain or get back the voltage in normal ranges after any contingency.

Frequency stability on the other hand denotes the ability of a power system to maintain system frequency within the specified operating limits. The frequency within an AC interconnected power system is dictated by the speed of the synchronous generators connected to it. In steady state, this frequency is the same throughout the system, equal or close to its rated value (i.e. 50 Hz in Curaçao). At the instant an imbalance between the generated and consumed active power occurs, the frequency alters as the power deficit or surplus is not instantaneously compensated by a corresponding increase or decrease in mechanical turbine power of the connected power plants. For satisfactory operation of the system, the frequency has to remain at all times within a narrow range around the rated value as specified in the grid codes. A substantial drop in the frequency will not only lead to high magnetization currents in transformers and induction motors, but may also detrimentally affect the performance of conventional power plants.

In large interconnected power systems, the frequency control is generally performed in different phases during which first the frequency is stabilized by a jointly droop controller reaction of all generators equipped with a speed controller or governor (i.e. so called primary control). Due to the proportional action, the frequency is stabilized during this process, yet still deviates from its rated value. The restoration of the frequency is accomplished in the next stage, also often called secondary control, by further adjusting the power setpoints of prime movers within selected units. This second control action is much slower than the governor action, with a time constant in the range of minutes. Due to the interconnection and size, those large power systems benefit from their large inertia and aggregated control of different power plants.

Islanded systems like Curaçao have inherently less inertia due to the limited number of connected units. Additionally, the implementation of primary and secondary control similar to large interconnected systems might not be preferred, but instead a single (or limited number) of machines are operated in isochronous control mode keeping the frequency always close to the rated value by means of a proportional-integral control scheme exchanging reserves with the system during power imbalances. Other units might be operated still in droop control or do not support in the frequency at all. Such operation entails different challenges to the frequency control as such (e.g. achieving a stable automatic coordinated control between different isochronous units) and to ensure an N-1 secure system (frequency stability in case of an outage of the isochronous unit(s)). In addition to the control of the generation units, the power balance can also be restored by controlling the load, i.e. demand response control of under frequency load shedding (UFLS). The latter cannot be considered as a standard means to stabilize the frequency, but rather as part of the defence plan, only to be activated in the case of extreme events (N-k) in order to avoid a further deterioration of the system state and/or blackout.

4.1.2. Generator controls and simulations (control loops)

To assess the frequency and voltage stability of the system, it is essential to have an adequate simulation model including a detailed representation of the different controllers in the network.

For the conventional generators, this should at least include:

- Detailed model of the generator (e.g. 6th order model) including its saturation
- Model of the Exciter and automatic voltage regulator (AVR) including its limiters, for instance:
    - Overexcitation limiter
    - Underexcitation limiters
    - Stator current limiter
    - V/Hz limiter
- Overlaying reactive power or power factor controller if applicable
- Power system stabilizer (PSS) if applicable
- Model of the governor and prime mover including overlaying ‘master’ controller managing e.g. the isochronous control over different units.
- Protection (feeder and decoupling relay)

A standard model can be built by requesting the block diagrams and parameters from the equipment manufacturer. To further validate the models and assess the performance of the conventional units, the following test can be performed (non-exhaustive list):

- For the generator: No load field saturation curve test, no load excitation test, load rejection tests, etc.
- For the AVR: Voltage step response tests, under and overexcitation limiter test (by changing reactive power setpoints or applying voltage steps at the terminals of the machine), etc.
- For the governor: Active power setpoint step response, Speed reference step response, Speed deviation step response, etc.

For the converter driven renewable energy units (e.g. wind turbines), a detailed model of the inverter and their controllers should be requested from the manufacturer including a detailed list of the parameters implemented during commissioning. As such models are mostly encrypted (to protect the IP of the manufacturer on the detailed control design), it is highly important to request a manual/detailed description of the parameter settings and the corresponding behavior of the unit. Specific tests can be defined to validate the required behavior and to benchmark the inverter model.

4.2. Analysis of received documents

4.2.1. Analysis of investigations reports

4.2.1.1. Manual switching of the control mode of power plants

Both the blackout of 11/02/2020 and 7/12/2020 were initiated by the manual switching of control mode on some units. On 11/02/2020, several units in the NDPP plant were inadvertently switched from over- to under excitation. On 7/12/2020, the control mode of units in Dokweg 2A was altered from isochronous/V droop to constant P/Q mode (reactive power setpoint was reduced).

Although these events should normally not lead to a black-out if proper protection and system control was put in place, it is preferred though that voltage and frequency control of units are prioritized as much as possible and inadvertently switching of control also needs to be avoided. Additional training of the plant personnel is required to increase the knowledge and trust in the current control set-up.

4.2.1.2. Fault ride through capability and reconnection

During several black-outs, it became clear that the fault ride through capability of the units is limited. Regarding wind turbines, it is recommended to revise their protections in order to assess whether a larger voltage and frequency withstand capability can be achieved and an alignment between the protection of different units can be made (i.e. change the settings of Playa Canoa and Tera Cora WF to resemble Tera Cora 2). For conventional units on the other hand, it is critical to keep the units as long as possible connected to the grid providing frequency and voltage support. Moreover, it is preferred to have the units limiting their output in case of overloading, rather than disconnecting.

Additionally, improvements are also required with respect to the automatic reconnection of the units by means of a more coordinated approach including reduced ramp rates. Alternatively, as suggested in the investigations report, reconnection of units could be performed manually only when voltage and frequency are stabilized around their nominal values.

4.2.1.3. Frequency and voltage control performance

Several blackouts, especially the one on 11/02/2020 and 7/12/2020 have revealed issues with the frequency and voltage stability/control of the system.

It is therefore recommended to first of all perform a detailed investigation on plant level to determine the frequency and voltage control characteristics in all power plants. Assessment of unit behaviour, i.e. if performance criteria are fulfilled, and benchmarking of the simulation models is required. The robustness of the controllers as well as the coordinated control of different units within the same plant also need to be analysed. “Hunting behaviour” between the Dokweg 2 units was for instance observed during the blackout of 11/02/2020 which could be caused by incorrect control design/tuning of the overlaying isochronous control.

On system level, it is important to review whether the implemented frequency and voltage control strategy is adequate to restore the voltage and frequency in due time before protection will be activated. Such assessment should be performed using an (RMS) simulation model of the whole system considering different contingencies (faults, outages of network elements, major loads or generation units) and different initial system states. The specific list of contingencies is usually defined in the operational and planning procedure/codes and may differ from system operator to system operator, however the selection is mostly based on a more generally defined security criterion, such as for instance the widely applied N-1 criterion. More extreme events should also be simulated in order to verify if the implemented UFLS scheme is properly designed to ensure timely intervention (i.e. load shedding) to avoid further deterioration of the system and as such avoiding a complete black-out.

4.2.1.4. *Review monitoring systems*

As highlighted in many of the blackout investigation reports, it is important to review the monitoring systems to make sure measurements are properly taken and stored. Especially for the event assessment and replication, it is essential to have an extensive view on the system state and its evolution before and after the blackout.

4.2.1.5. *Blackout event replication*

The investigation reports are only based on measurements, but do not include any replication of the event through simulation. It is considered highly important though to perform such event replication, not only to validate the available simulation models (and revise where needed), but also to support the assessment of possible mitigation measures.

4.2.2. Analysis of other received documents

4.2.2.1. *Technical Limits and Requirements for installing large scale Photovoltaic and Wind Generation in the Aqualectra Power System (DIgSILENT, 2014)*

Some relevant recommendations were provided related to power system stability and control in the study performed by DIgSILENT in 2014. It mostly focuses on defining operational criteria considering an increase in renewable energy penetration of wind and PV (with an expected total of 97 MW installed renewable capacity at that time). A maximum in-feed of fluctuating renewable sources was defined in function of the minimum loading of diesel units and their spinning reserve requirements. It is unclear though whether Aquaelectra has implemented those criteria in their operational procedures or defined another stability criteria (e.g. minimum number of synchronous based units in service).

Secondly, the study also provides recommendations to facilitate the integration of more renewable generation like adding synchronous condensers (or converting existing synchronous units to synchronous condensers) to provide the required inertia, short-circuit (system strength) and reactive power. To minimize the grid frequency fluctuations due to the fluctuating RES injection, an automatically, fast acting secondary control system shall be installed according to the report.

Thirdly, also recommendations are provided related to the modeling of the system, and more specifically regarding the load. It is advised that load measurements at representative feeders shall be implemented in order to determine the load characteristics more precisely in terms of frequency and voltage dependency as well as their motoric/static mix including load inertia.

4.2.2.2. *Beschouwing balanshandhaving en spannings- en frequentieregeling Aqualectra net (DNV GL, 2021)*

In this report of DNV, the implemented voltage and frequency control strategy is presented. Although a good general overview is given, no details on the specific implementation, their corresponding control models and parameters are discussed. In line with the outcomes from the investigation reports, it is important to:

- Model the different controllers in detail, benchmark the models with real system measurements (or tests) and assess their robustness in different operating conditions. Especially the coordinate approach to provide isochronous control is prone to stability issues if not well tuned.

- Develop a clear understanding and knowledge building within the operational teams on the way the different automatic controllers interact and what the impact is on a manual intervention (e.g. the effect of changing the taps within the 66/30 kV transformers on the reactive power flow distribution and associated voltage control)

4.3. List of recommended actions listed in the reports and follow-up

This section summarizes the most relevant actions that were listed in the document provided. From these documents, the status of these recommended actions was not always clearly indicated. Aqualectra provided clarification when reviewing the draft version of this report. This clarification is included in the status column.

Action	Report	Status[6]	Comment
Further investigation requires to review frequency and voltage regulation	Blackout event recovery actions table in “20210201 Report-Root-cause_analysis-Blackout-events”	*“This is covered by the security of supply study. “*	Table says that DNV is performing a voltage stability study
Consult with WT supplier to optimize FRT	DNV report 8 and 15 June + Blackout event recovery actions table in “20210201 Report-Root-cause_analysis-Blackout-events”	“*This was consulted with Vestas, and there are limitations to the inverters. It's good to note that in a small grid with high renewable generation, the system will lack reactive power. Therefore, the grid stability study was done, and Aqualectra must install fast BESS to guarantee stability.*”	Playa Canoa & Tera Cora I disconnected (V < 0.9pu for 3s) but not Tera Cora II
Reconnection of WF leads to over-frequency	Blackout event recovery actions table in “20210201 Report-Root-cause_analysis-Blackout-events”	*“This was discussed with Vestas, and Aqualectra has taken the necessary measures to prevent the wind park from going online automatically after a disturbance.”*	
Improve monitoring systems	“20210201 Report-Root-cause_analysis-Blackout-events”	*“The PFM monitoring system will be installed at all substations on all 66, 30, and 12 kV feeders. In January 2024, Aqualectra installed PFM’s at substations Tera Cora and Brievengat. By the end of 2026 all substations will be*	

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[6] *As communicated by Aqualectra in the document “Comments on Laborelec reports.pdf”*

Action	Report	Status[6]	Comment
		equipped with a PFM system.“	
Detailed investigation to determine frequency and voltage control characteristics in all power plants is required. Assessment of unit performance with respect to overall system control strategy, i.e. if performance criteria are fulfilled.	“20210201 Report-Root-cause_analysis-Blackout-events”	*“This was covered in the grid stability and security of supply study.“*	
Define criteria for maximum renewable power injection	Technical Limits and Requirements for installing large scale Photovoltaic and Wind Generation in the Aqualectra Power System, 2014	*“With respect to defining criteria for maximum renewable power injection: Digsilent performed a study in 2023 on a Battery Energy Storage System, addressing operation reserves, contingencies, system inertia (RoCoF), grid strength (short circuit ratio) with an increase of wind energy, addition of central PV and a battery storage system to improve inertia.”*	“The maximum in-feed of fluctuating renewable resources in function of the min. loading of diesel generators and the spinning reserve requirements”
Aqualectra shall analyse the options to convert generators to synchronous condenser	Technical Limits and Requirements for installing large scale Photovoltaic and Wind Generation in the Aqualectra Power System, 2014	*“In 2005 KEMA analysed such conversion (KEMA report 40510003-TDC 05-49809A "Vooronderzoek ombouw generator T8 tot synchronous condenser"). As a result, it was concluded that in Aqualectra's situation, the BESS system is better compared to the synchronous condenser.”*	Analysis from 2005. It would be worth to re-assess this option.
Aiming in minimizing the grid frequency fluctuations due to the fluctuating RES injection, an automatically, fast acting secondary control system shall be installed	Technical Limits and Requirements for installing large scale Photovoltaic and Wind Generation in the Aqualectra Power System, 2014	*“Based on the study, Aqualectra should install a BESS system of a minimal 25 MW, 25 MWh that has a fast reaction to guarantee the stability of the grid.”*	
Check settings of AVR and Governor at Dokweg	DNV report 27 July 2023		

Action	Report	Status[6]	Comment
Perform or review steady state and dynamic simulations with different scenarios	DNV report 8 and 15 June 2023	*"This was done in May of 2023 with the load data of 2022. Now we are working on the data for 2023 to run the simulations with data for 2023. The worst-case scenario, which is maximum load and no renewable energy, is being used; this is our worst-case situation for the 66 and 30 kV grid."*	In systems with high penetration of renewable energy, it is not sufficient to work with one worst-case scenario. Multiple relevant scenarios have to be analyzed.
The additionally required reactive power shall preferably be provided on basis of a synchronous condenser featuring additional high short circuit power	Technical Limits and Requirements for installing large scale Photovoltaic and Wind Generation in the Aqualectra Power System, 2014	*"A synchronous condenser can indeed provide high short-circuit power, but from a financial point of view, it's not feasible. A BESS system is more convenient for Aqualectra than the synchronous condenser."*	It is correct that synchronous condenser is not the only solution and that BESS is also a valid technical option, therefore the most economical solution has to be chosen. However, it has to be noted that protection settings of overcurrent protection in systems with very few rotating machines is more complex. Also, inadequate control of the BESS might lead to stability issues.
When replacing synchronous machine based generation by inverter based power injection, the available reactive power is reduced unacceptable resulting in a lag of reactive power of some 20 MVAr	Technical Limits and Requirements for installing large scale Photovoltaic and Wind Generation in the Aqualectra Power System, 2014	*"Based on the grid stability study, we are aware of the lack of reactive power, and this will be supplied by the BESS system."*	
Ensure proper working and understanding of isochronous operating system	"20210201 Report-Root-cause_analysis-Blackout-events"	*"In 2021, the isochronous system was still new for our operators, and there were some technical challenges with the system, given it was a new technology. Now our operators have a much better understanding of how the system works."*	

Table 2: List of actions (from analyzed reports) regarding power generation and stability

4.4. Our main recommendations regarding power generation and system stability

In summary, when analyzing all the provided documents, the following main recommendations are given related to power system stability and control:

- Wind turbine protections shall be further reviewed and new settings shall be implemented. These protections should also be integrated in the current power system model (e.g. in PowerFactory) in order to perform dynamic simulations to assess system security.
- Diesel units control: robustness of control parameters (related to voltage and frequency control) shall be further analyzed via simulations or field tests. Moreover, switching of control mode should be included in a dedicated procedure.
- Diesel units protections: it is preferred to have the units limiting their output in case of overloading (rather than disconnecting). Generally, it is important to keep critical units as long as possible connected to the grid. This point was not mentioned in any of the reports but we recommend to discuss with the manufacturers to see what are the possibilities.
- Stability: it is unclear whether there is a stability criterion, such as minimum inertia or a minimum number of diesel units running, is used in daily operations. This is critical to assess during high wind production, and has also an impact on the short-circuit current (used in the protection settings).

5. Task 3: Focus on organization and procedure

5.1. Best practices

5.1.1. Operational security

5.1.1.1. What is operational security?

The main goal of operational security is the following: “No cascading failure from a single event”.

According to[7], this leads to one main obligation, which can be defined as followed:

Obligation for the system operator to monitor the consequences of the events defined in its contingency list and identify whether its system is at risk.

By consequent the organization and procedures must be in place to guarantee that the system operator will do its best efforts to set-up remedial actions and **be aware of the risks** (even if not sufficiently covered).

5.1.1.2. Definition of a contingency list

A contingency list contains the main disturbances that can occur on the system (generation and transmission). This can therefore be cable faults, busbar fault, loss of generating units, etc.

From the historical blackouts, it seems that at least the following types of events shall be considered in the contingency lists:

- Contingency on generation:
    - Loss of a single generating unit
    - Loss of multiple generating units
    - Change of operating mode of selected generating units
- Contingency on transmission elements
    - Fault followed by N-1 on 66kV cable
    - Fault in 12 or 30kV cleared by back-up protection
    - Fault close to wind farms (including model of under-voltage wind turbine protections).

Typically, the events of the contingency list are simulated on a power system model (including overcurrent protection, under/over-voltage protection & under/over-frequency protection settings of grid assets and generating units), and control loops indicated in section 4.1.2. It is important to ensure that adequate modelling and simulations are used, depending on the type of events and phenomenon under study. These simulations should ideally be performed as regularly as possible and using forecasted operating conditions.

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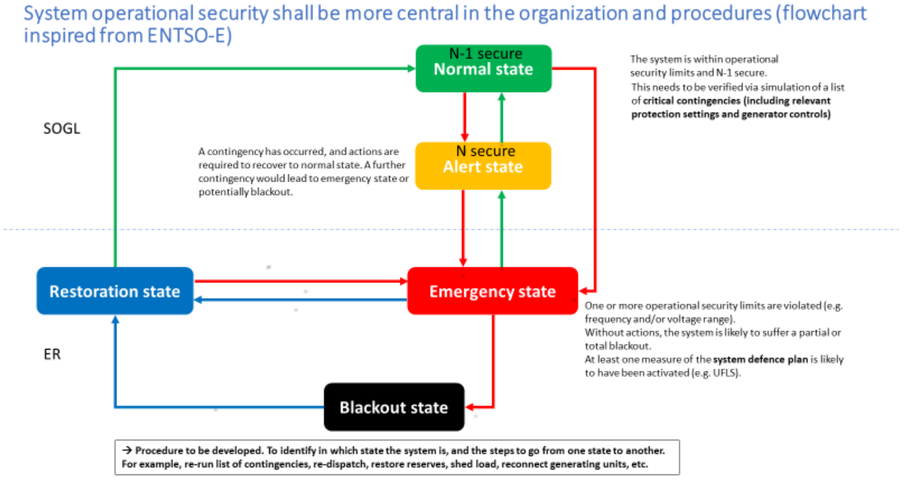
[7] *https://eepublicdownloads.entsoe.eu/clean-documents/pre2015/publications/entsoe/Operation_Handbook/Policy_3_final.pdf*

5.1.1.3. Definition of system state

In order to improve the **risk awareness** and also clarify which sets of procedures need to be followed in each system state, it is important to define the system state in operations. Figure 14 illustrates the five operating states typically used in system operations (inspired from ENTSO-E). These states can be defined as followed:

- **Normal state**: the system is within operational security limit and N-1 secure. N-1 security is verified via simulations of a list of critical contingencies.
- **Alert state**: the system is within operational security limit. However, a contingency from the contingency list would lead to emergency state or black-out state
- **Emergency state**: One or more operational security limits are violated (e.g. frequency and/or voltage range), without actions, the systems is likely to suffer a partial or total blackout. In this state, at least one measure of the defense plan is likely to have been activated (e.g. UFLS).
- **Blackout state:** complete interruption of power in the transmission system.
- **Restoration state:** state in which the main objective is to re-energize the power system and restore supply to all loads.

More detailed information on the Normal and Alert state can be found in the System Operations Guidelines of ENTSO-E[8], while more detailed information on the Emergency, Blackout and Restoration states can be found in the Emergency and Restoration Guidelines[9].



System operational security shall be more central in the organization and procedures (flowchart inspired from ENTSO-E)

The system is within operational security limits and N-1 secure.
This needs to be verified via simulation of a list of **critical contingencies (including relevant protection settings and generator controls)**

A contingency has occurred, and actions are required to recover to normal state. A further contingency would lead to emergency state or potentially blackout.

One or more operational security limits are violated (e.g. frequency and/or voltage range).
Without actions, the system is likely to suffer a partial or total blackout.
At least one measure of the **system defence plan** is likely to have been activated (e.g. UFLS).

→ Procedure to be developed. To identify in which state the system is, and the steps to go from one state to another. For example, re-run list of contingencies, re-dispatch, restore reserves, shed load, reconnect generating units, etc.

Figure 14: Flowchart system operational states (inspired from System Operation Guidelines and Emergency & Restoration guidelines from ENTSO-E)

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[8] *https://www.entsoe.eu/network_codes/sys-ops/*

[9] *https://www.entsoe.eu/network_codes/er/*

5.1.1. Restoration procedure

5.1.1.1. Restoration phases

While restoration concepts vary from one system to another (each system having its own specificities), it is generally agreed that restoration procedures can be grouped into the three following phases (inspired from[10]):

- **Phase 1: Diagnosis**
- In this Phase 1, the extent of the blackout is assessed. It is also evaluated whether equipment are damaged and which operating procedure is the most adequate to re-energize the grid.
- **Phase 2: Activation of the re-energization procedure**
- In this second phase, the aim is to re-energize the grid from the key generating stations and to restore supply to target loads (e.g. critical industries, key substations, etc. until a stable grid is formed.
- **Phase 3: Restoration of the loads**
- The third phase involves the successive restoration of all loads.

It is difficult to evaluate the duration and complexity of each of these phases. However, it would be interesting to have a return on experience from historical blackouts in order to evaluate whether one phase could be done quicker in the future.

5.1.1.2. Zonal vs backbone restoration

A backbone restoration consists of:

- Restart of the key (black-start capable) power plants
- Energization of a cranking path to re-energize auxiliary units of non-black start units
- Restoration of loads

A zonal restoration consists of:

- Restart of power plants with black start capabilities in each zone
- Load restoration within each zone until stable loads are obtained
- Interconnection phase

Zonal restoration has several advantages in networks where multiple units can be restarted simultaneously. It also allows to have alternative paths in case of damage of the electrical assets.

Backbone restoration is preferred in systems with large generating units (e.g. large hydro) but requires the units to be able to absorb a significant amount of reactive power.

In island networks, both options are possible depending on the technical capabilities of the generating units.

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[10] *https://www.elia.be/-/media/project/elia/elia-site/public-consultations/20181005_consultation_document_1_note_a_review_blackstart_2018_en.pdf*

5.1.1.3. *Soft energization*

Soft-energization allows to avoid inrush current when energizing transformers.

Typically, circuit breakers are closed between the generator, the step-up transformer and potentially other transmission assets before energization. The generator terminal voltage is then gradually increased to nominal values. This method has a big advantage in terms of inrush but requires dedicated protections settings.

5.2. Analysis of received documents

5.2.1. Analysis of investigations reports

The main remarks regarding the organizational and procedure aspects in the investigation reports are the following:

- **Lack of risk awareness**. In none of the documents, it is mentioned whether pre-event conditions are N-1 secure. It is only described that pre-event conditions are within the voltage and frequency range. However, this does not guarantee that the system is N-1 secure. In other words, it should be stated whether the system is in the **Normal State or in the Alert State**.
- **No investigation on restoration**. The analysis of the restoration should be part of a blackout investigation (blackout situation is finished only after restoration).

5.2.2. Analysis of other received documents

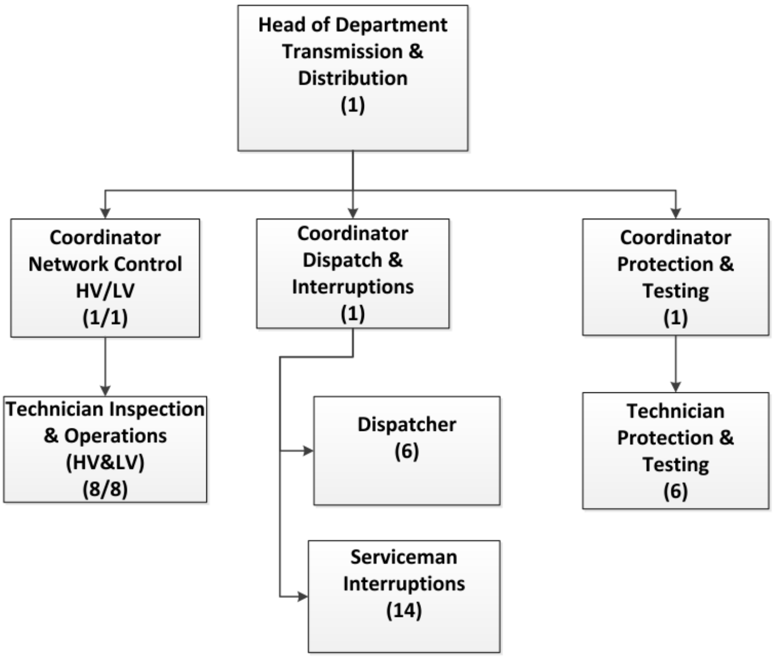

Figure 15: Organigram T&D department

In the other documents received, our main focus was to analyze in the organigram who were the persons responsible for the "Operational Security" of the system. However, we could not find clearly a function with that responsibility.

- In the document “Functieboek Power Supply Chain_Final_15005202210”, no clear roles/job descriptions are given for the operational aspects on system level, associated to power system security assessment in day ahead planning or real time operation.
- One would expect, it is part of the job description of the functions presented in Figure 15, however it seems that these functions focus merely on the assets itself (maintenance, repair, monitoring of individual network elements or plants) or are involved in curative actions after power interruptions (sending teams out, solve the interruption, …). **Operational tasks associated with optimal resource planning on system level are missing**, i.e. scheduling/dispatch of the power plants and control of the network configuration taking into account security constraints:
    1. **Head of Department Transmission & Distribution:** Bewaakt het functioneren van distributie netwerken en draagt zorg voor verbeter maatregelen om tekortkomingen en storingen te verhelpen. → managerial function
    2. **Coordinator Network Control HV/LV District I/II:** Garandeert gepaste bediening van de HV en LV netwerk installaties → asset level
    3. **Technician Inspection & Operations (HV&LV):** Voert planmatige inspecties en kwaliteitsmetingen uit van netdelen en installaties alsook inspecties van gebouwen en terreinen. → asset level
    4. **Coordinator Dispatch & Interruptions:** Zendt teams uit, coördineert en begeleidt in het oplossen van stroom onderbrekingen. → dispatch of people/teams, not power plants/network elements.

The outage & capacity planning document has also been looked at. It could be observed that the outage of the generating units are well planned and follows a clear and well defined schedule. However, no information was received on transmission Assets. It could therefore not be verified whether the outage scheduling is also well planned and organized for the switchgears, transformers, cables, etc.

It should also be noted that we had the verbal confirmation that Aqualectra personnel follows adequate training from DigSilent (e.g. such as protection and system simulations). However, it could not be verified whether a formal training plan was in place.

5.2.3. List of actions listed in the reports and follow-up

This section summarizes the most relevant actions that were listed in the document provided. From these documents, the status of these recommended actions was not always clearly indicated. Aqualectra provided clarification when reviewing the draft version of this report. This clarification is included in the status column.

Action	Report	Status[11]	Comment
Prior to the blackout, line Dokweg 66kV-Parera was out-of-service, hence all generation from Dokweg 2 power plant was being exported through line Dokweg	Analysis of Grid Events - 12.12.2020	“*Given the fact that Aqualectra’s 66/30kV, 65MVA transformers must be energized by means of a soft start, and Aqualectra can't soft start the whole 66kV grid at once. Aqualectra must energize it*	Main question here is: how do you verify n-1 security?

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[11] *As communicated by Aqualectra in the document “Comments on Laborelec reports.pdf”*

Action	Report	Status[11]	Comment
66kV-Isla 66 kV. This operation has revealed as not N-1 secure with very critical consequences for system stability. Therefore, it is recommended to review operational practices		*in two separate soft starts and synchronize these two grids. On the morning of December 12, Aqualectra performed a soft start from Dokweg 2, but Aqualectra couldn't synchronize the two grids, so Aqualectra had to stop the soft start. Nowadays, Aqualectra has adapted its soft start sequence so that this issue does not exist anymore. So yes, Aqualectra was no longer N-1 with the transformer of Parera out of service. This will also be covered in the grid structure study, the N-1 situations."*	
A strategy and procedure for controlling the voltage 66kV voltage after a blackout shall be prepared for.	DNV report 8 and 15 June	*"Aqualectra is aware of this, and it's a procedure of adapting the tap changer of the 66/11 kV and 66/30 kV transformers. This process takes a couple of days to get the voltage back to the nominal value."*	
Perform or review steady state load flow and dynamic simulations with different scenarios to identify system vulnerability and weak points.	DNV report 8 and 15 June	*"The steady-state simulations were realized with the peak load of 2022. Now Aqualectra is working on the 2023 data to run the simulations again. This will be a yearly activity."*	Proposed action in-line with the best practices on operational security.

Table 3: list of actions (from analyzed reports) regarding procedures and organisation

5.3. Our recommendations regarding organization and procedure

Operational security

It is advised that an operational security assessment becomes an inherent part of operating the power system of Curacao. Applying the standard N-1 principle, such assessment may for instance involve the following steps:

- **Evaluating the system state**: Define the status of the system taking into account a pre-defined contingency list and simulation results.

- **Contingency list**: Compose a contingency list with normal and exceptional contingencies considered relevant according to the operator risk assessment.
- **Operating limits**: Define the allowed loading, voltages, angle differences, etc. within the system in normal operation or for a limited amount of time considering the curative remedial actions taken after contingencies.
- **Remedial actions**: Define and list the possible remedial actions, i.e. measures applied in due time by the system operator in order to fulfil the N-1 security principle of the transmission power system. Those could be preventive or curative.

Ideally this assessment should be included in operational day ahead planning and real time operation (repeated every 15 min). However, having this assessment done offline on a regular basis (e.g. weekly on selected representative operating conditions) shall already be a significant improvement in terms of risk awareness (dispatchers should have a clear view on the system state and its security (e.g. alarms if system is not N-0/N-1 secure)).

Incorporating such operational security assessment within Aqualectra requires updated/additional operational standards, procedures, a formal training program, etc. and also most probably a reorganization (or creation) of some functions in the T&D department. This therefore requires full support from the higher management.

Power system restoration

Power system restoration is an integral part of system operations. It is therefore recommended to include a detailed analysis of the restoration process into the future blackout investigations. It is especially important to understand whether the restoration time can be speed up, and if not, what are the limitations (e.g. technical, resources, etc.). Ideally, targeted restoration times should be pre-determined for each of the restoration phases as indicative values (restoration time can indeed vary depending on the actual cause of a blackout) and investments shall be identified if some restoration phases would need to be speed up.

Follow-up list of recommended actions

In each of the received documents (written by DNV or DigSilent), there is a list of valuable recommended actions. However, it is not always clear what has been done and which function/team is responsible for these actions. This can indeed be internal to Aqualectra and does not have to be in the Consultant report. However, it is important to track these actions and also clearly identify whether some recommendations are challenging to implement (e.g. due to lack of specific profiles or lack of trainings, not possible technically, etc.).

6. Conclusions and recommendations

This section summarizes our main findings and recommendations.

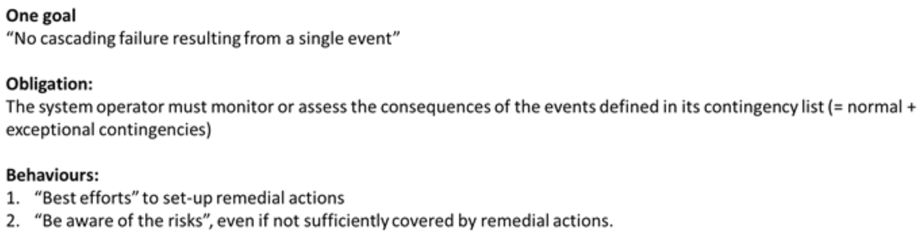
1. Regarding the investigations reports:
    a. **The investigation reports follow a sound approach and are from our point of view technically correct**. For example, the observations on protection settings are correct and it is justified to improve the settings and protection philosophy.
    b. **Follow-up of recommendations and current status not always clearly tracked**. There are many parallel ongoing tracks (security of supply, contingency analysis, protection studies, etc.) and a formal reporting process should be used to evaluate the status and impact of each task.
    c. The scope of work of the blackout investigations **is from our point of view too narrow**, focusing only at technical facts. There are a few important points to consider:
        i. None of the reports confirms or not whether the initial operating point (i.e. before the event) was acceptable in terms of security (e.g. N-1 secure).
        ii. None of the reports shows a replication of the events using simulations.
        iii. Timing for the investigations and implementation of the actions. For example, if investigations of December blackouts 2020 had been faster, this would most likely have avoided the January 2021 blackout.
        iv. Restoration aspects are not covered.
2. Regarding **protections:**
    a. Protection settings (for generators and transmission assets) should be stored in a database and verified via simulations using operating conditions from SCADA snapshots.
    b. Calculations of overcurrent protection settings (minimum short-circuit current) should be based on multiple scenarios taking into consideration the dispatch. This is most probably not done for a sufficient number of scenarios.
3. Regarding **power generation & stability:**
    a. Wind turbine protections shall be reviewed, and if possible, included in a model (e.g. in PowerFactory). Dynamic simulations should be performed including these settings to assess system security.
    b. Diesel units control: robustness of control parameters shall be further analysed via simulations or field tests. Moreover, switching of control mode should be included in a dedicated procedure.
    c. Diesel units protections: it is preferred to have the units limiting their output in case of overloading (rather than disconnecting). Generally, it is important to keep critical units as long as possible connected to the grid. This point was not mentioned in any of the report but we recommend to discuss with the manufacturers to see what are the possibilities.

    d. Stability: it is unclear whether a stability criterion such as minimum inertia or a minimum number of diesel units running is used in daily operations. This is critical to assess during high wind production, and has also an impact on the short-circuit current (used in the protection settings).

4. Regarding **organization and procedures:**
    a. **Training programs**. From the discussions we had with the technical teams, we had a positive impression on the level of technical knowledge. It was also positive to see there were training organized with DigSilent for protections and system simulations (static and dynamic). However, we received no evidence whether there is a formal training program for the experts in charge of protections and the experts in charge of verifying the operational security of the power system.

    b. **List of recommended actions should be closely followed-up**. This might be already the case but we could not verify this from the documents provided.

    c. From **the organizational point of view**, it seems that the functions and procedures are more focused towards maintenance, field interventions, coordination of technicians, etc. which is very valuable and this is similar to what we see for distribution system operators. However, with the increasing penetration of renewable energy, operation of a power system is more complex and we would recommend to create at least one additional role focusing only at the **operational security of the power systems** (i.e. drafting operation guidelines, verifying operational security via simulations, etc.). See here below a summary of the objectives of operational security (under N-1 criterion, inspired from [Microsoft Word - Policy 3 after public consultation_final_v2 (entsoe.eu)]):



One goal
"No cascading failure resulting from a single event"

Obligation:
The system operator must monitor or assess the consequences of the events defined in its contingency list (= normal + exceptional contingencies)

Behaviours:
1. "Best efforts" to set-up remedial actions
2. "Be aware of the risks", even if not sufficiently covered by remedial actions.

From the provided organigram, it is believed that including operational security might need to reorganize the T&D team or create a new function.

    d. **Restoration should be included in blackout investigation reports**. Also, targeted restoration times should ideally be pre-determined for each of the restoration phases as indicative values (restoration time can indeed vary depending on the actual cause of a blackout). If possible, investment should be identified and quantified if required to speed up the restoration process (e.g. UPS for critical IT systems, point of wave circuit breaker switching, synchronous condenser mode for Dokweg units, etc.)