Description and analysis of the Hagby incident, 26th April 2023

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Agenda

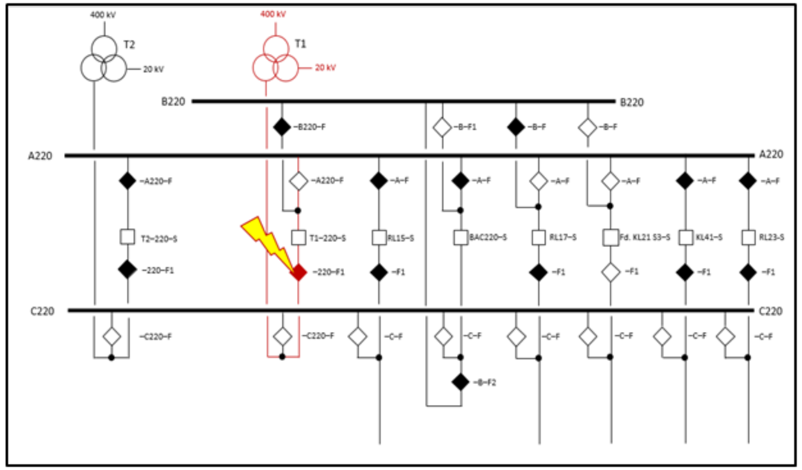
> Sequence of events
> Disturbance and fault-clearing
> Analysis of the post-fault events
> Frequency analysis and model validation
> Conclusions

Sequence of events

Operation state: Normal

Planned maintenance work in Hagby substation

Low loading and good margins to handle a N-1 contingency



A disturbance is caused by the opening of a disconnector under voltage: fault-clearing takes 7 (!) seconds

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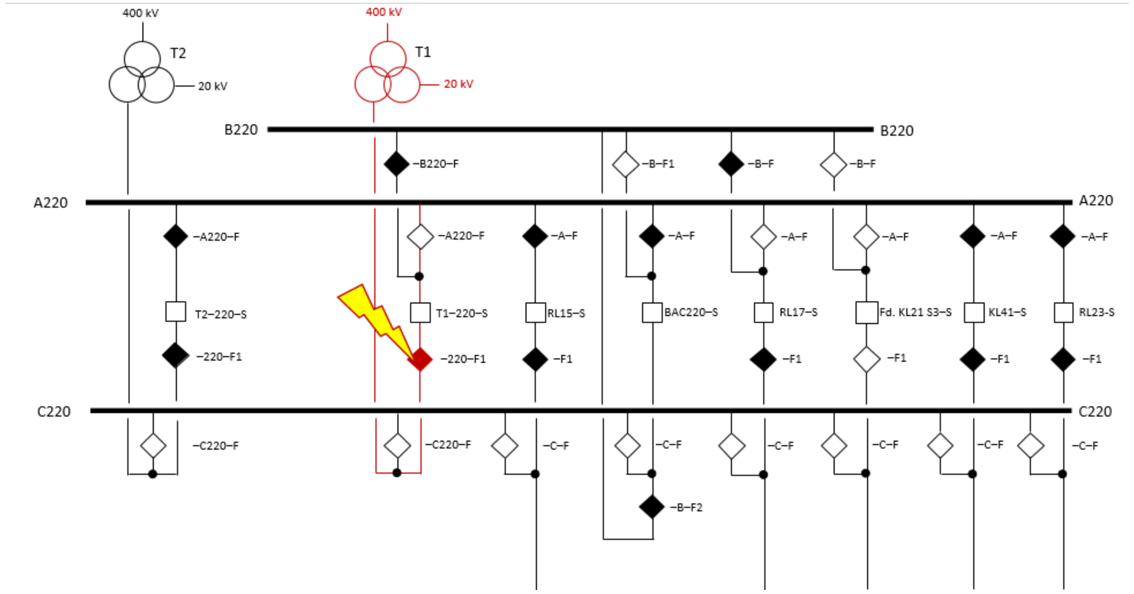
Disturbance and fault-clearing

Fault sequence

1) Remote maneuvering of a disconnector did not work as intended and de-blocking from the control room was initiated
2) The de-blocking allowed maneuvering of the *wrong* disconnector which still had load current, causing a lightning arc and short-circuit
3) Busbar protection were instantly activated, opening all 220 kV circuit breakers
4) Because of two independent errors in the station, the circuit breaker at T1 did not receive a trigger pulse, causing the fault to remain for 7 (!) seconds
5) A zero (U_0) voltage protection finally cleared the fault



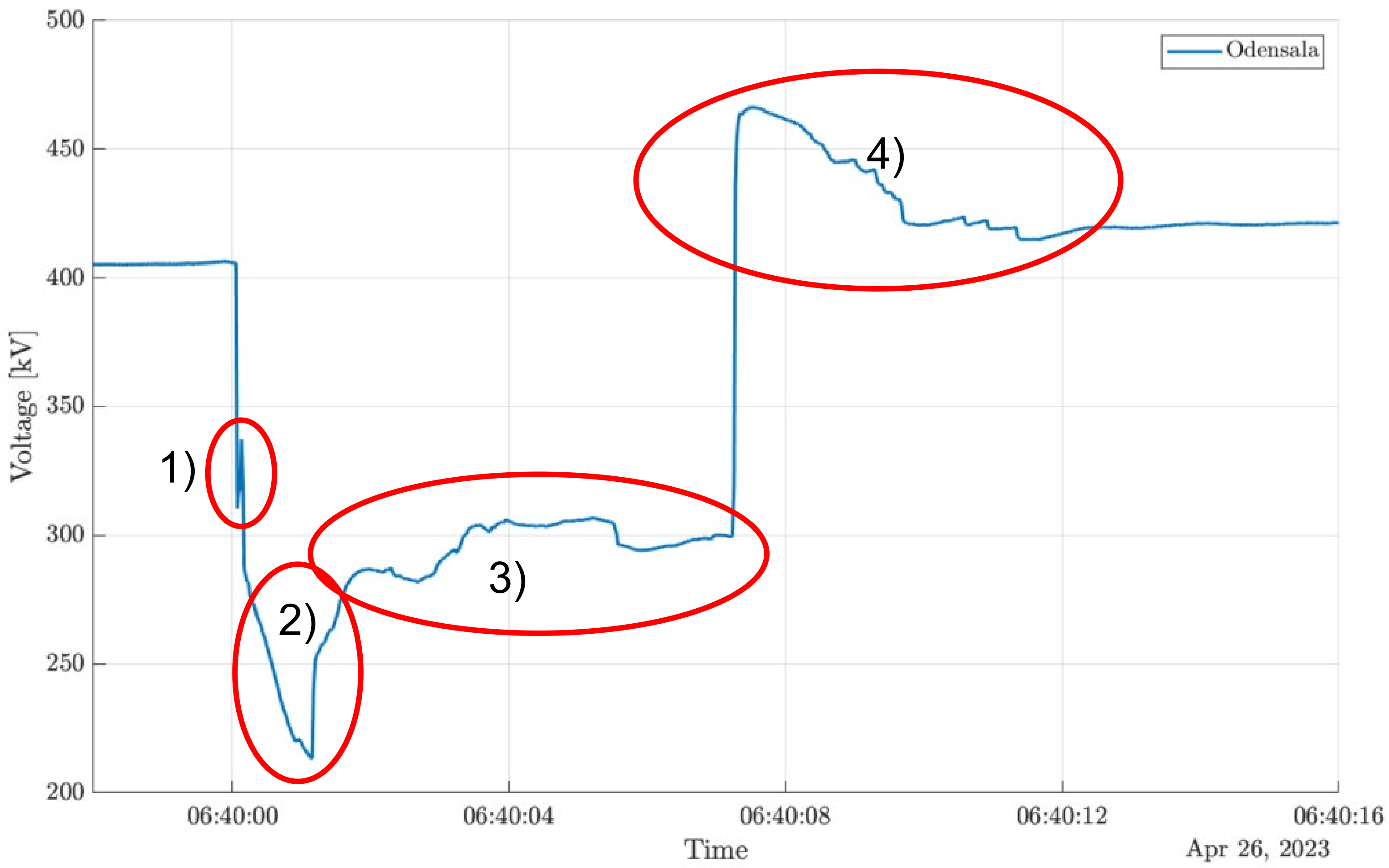
Analysis of the post-fault events

Phase 1: Two-phase into three-phase fault

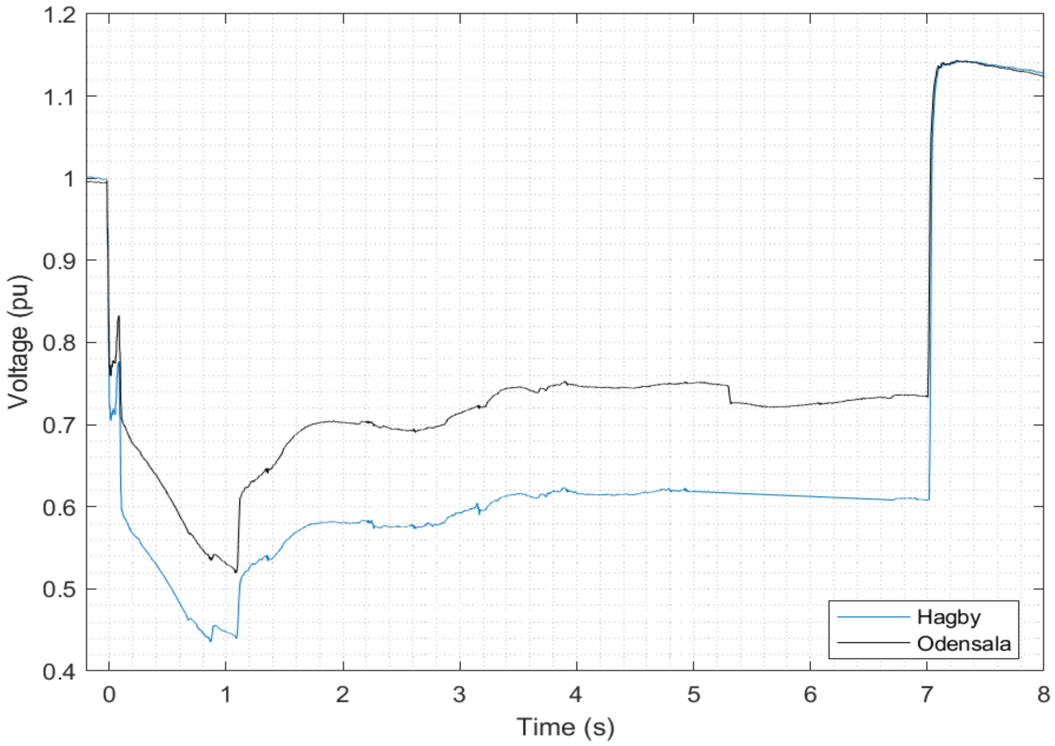
Phase 2: Voltage degradation and disconnection of generators

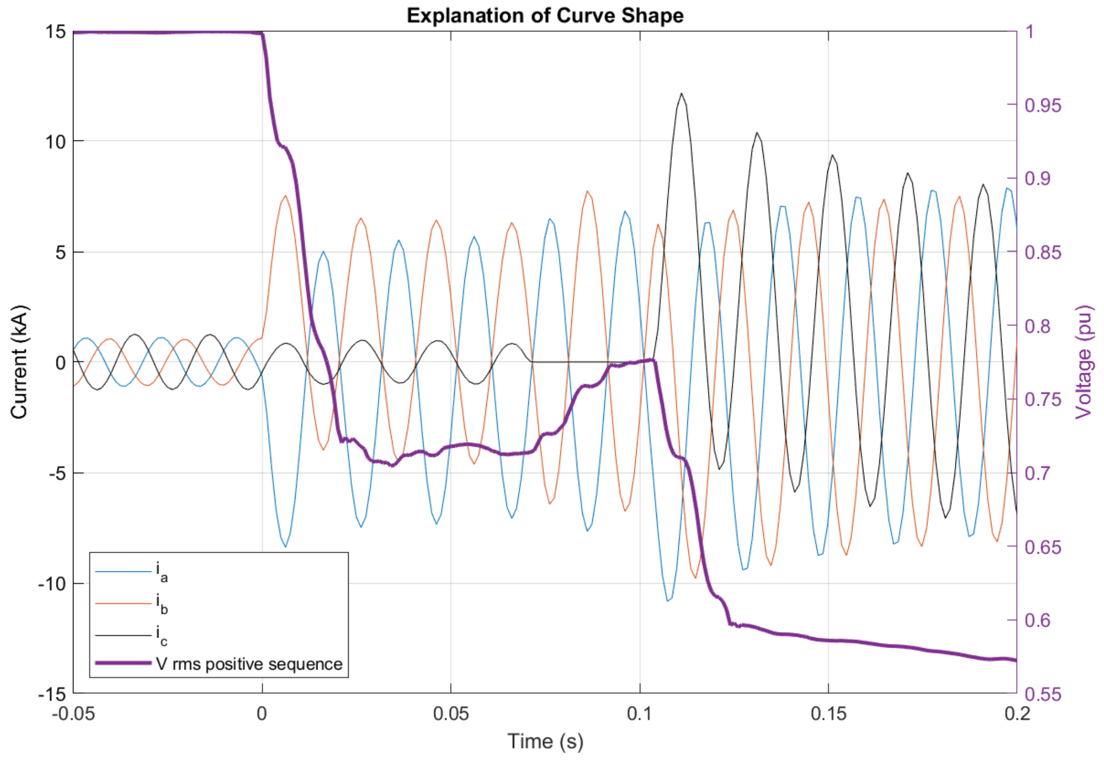
Phase 3: Reactive power support and emergency protection

Phase 4: Fault-clearing and post-voltages



Phase 1: Two-phase into three-phase fault





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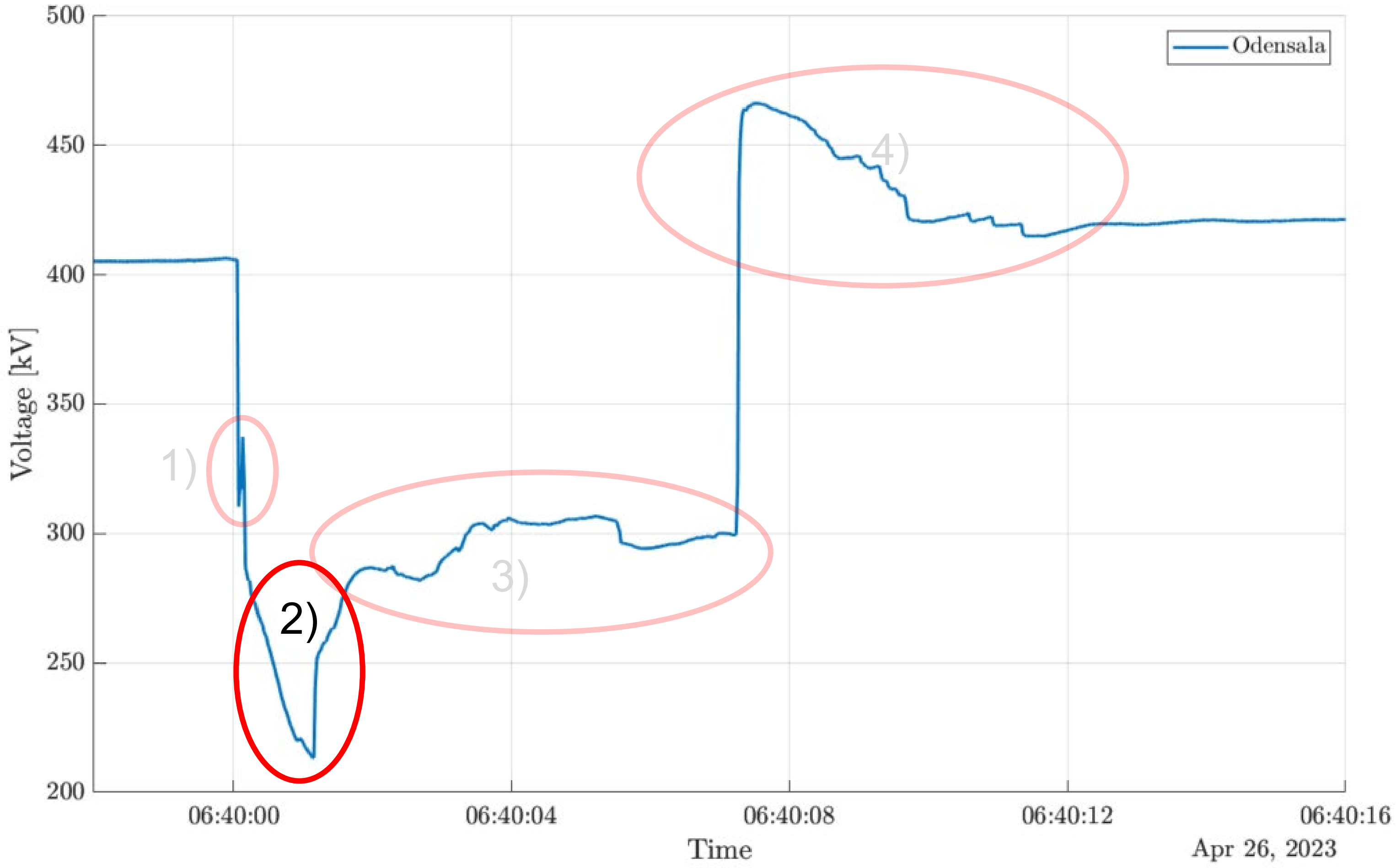
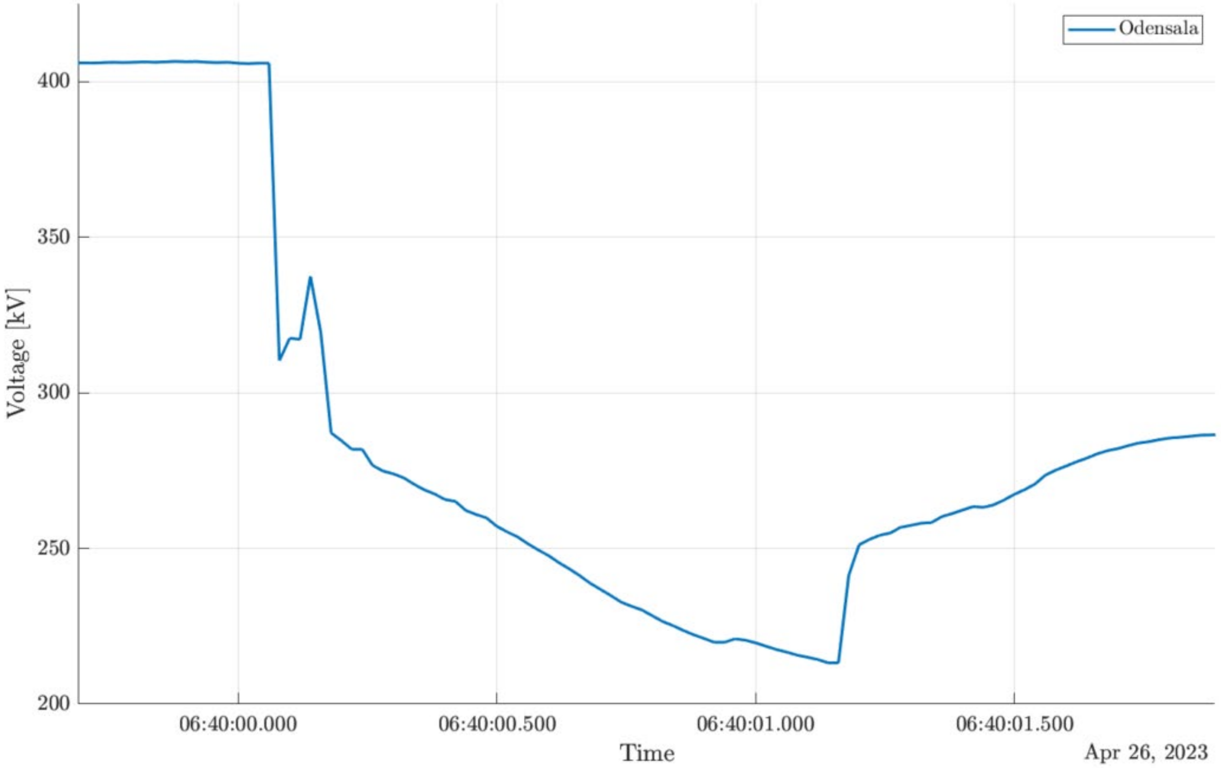


Phase 2: Voltage degradation and disconnection of generators



Decline in post-fault voltage is caused by:

> Sub-transient (X''_d) → transient (X'_d) → synchronous (X_d) reactance of the generators

> Higher reactance → higher voltage drop

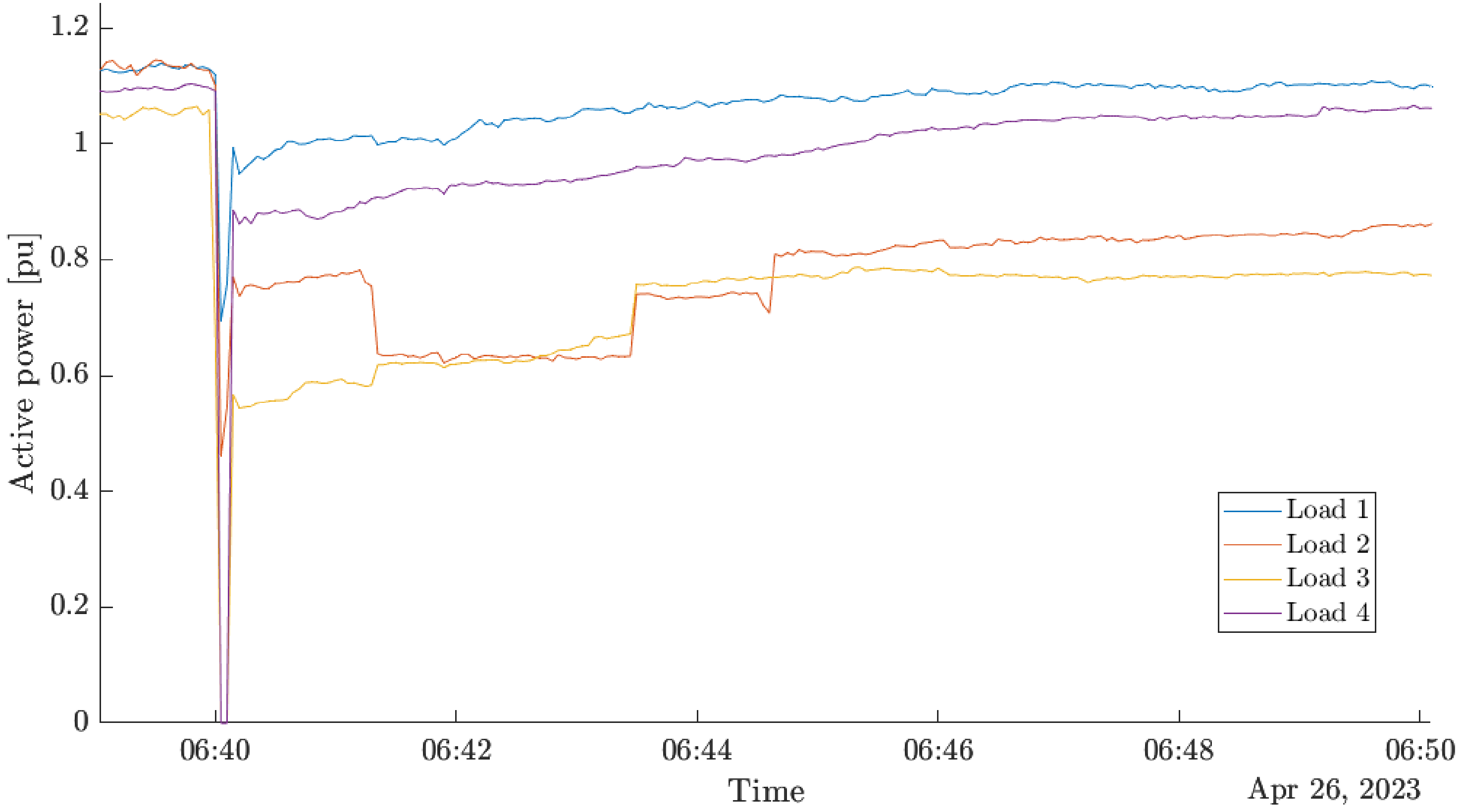
Generators disconnections:

> Forsmark 1 (G11 and G12) disconnect at ~0.8-1s after the fault

> Forsmark 2 (G21 and G22) after ~1.2 s

> Several other smaller generation units disconnects as well

Phase 2: Load dynamics

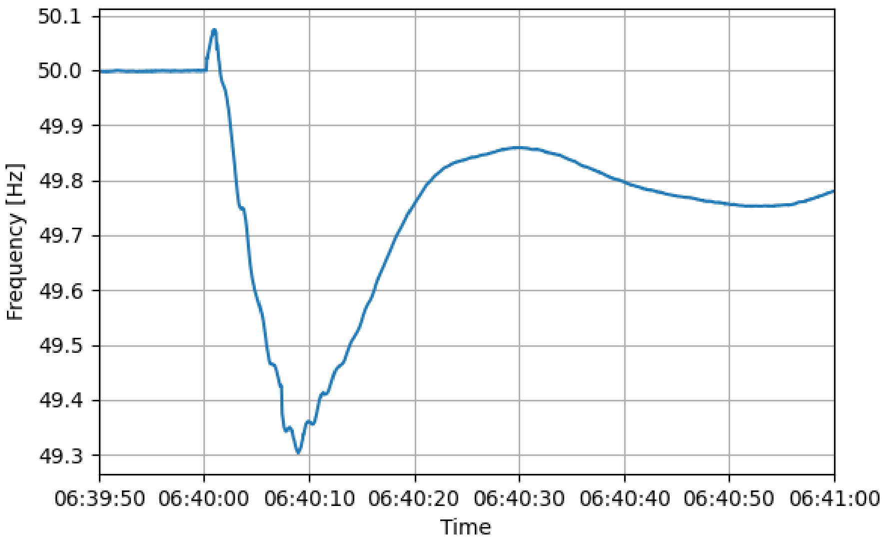


Voltage- (and frequency-) dependent loads act to stabilize the system voltages

> Several loads are being completely disconnected from the system

> By analyzing only the 7 (electrically) closest substations to Hagby, the total load was reduced by ~360 MW (3 s after the fault)

> Over time, loads are being restored back to nominal values



Phase 2: Simulations results

System behavior can be (relatively well) replicated through dynamic simulations

> Difficult to perfectly replicate the pre-disturbance state to a dynamic simulation

> Load dynamics are relatively unknown: ZIP-models are not providing the ”full picture”

> These type of events provide us with possibilities to enhance and validate our models

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Analysis of the post-fault events

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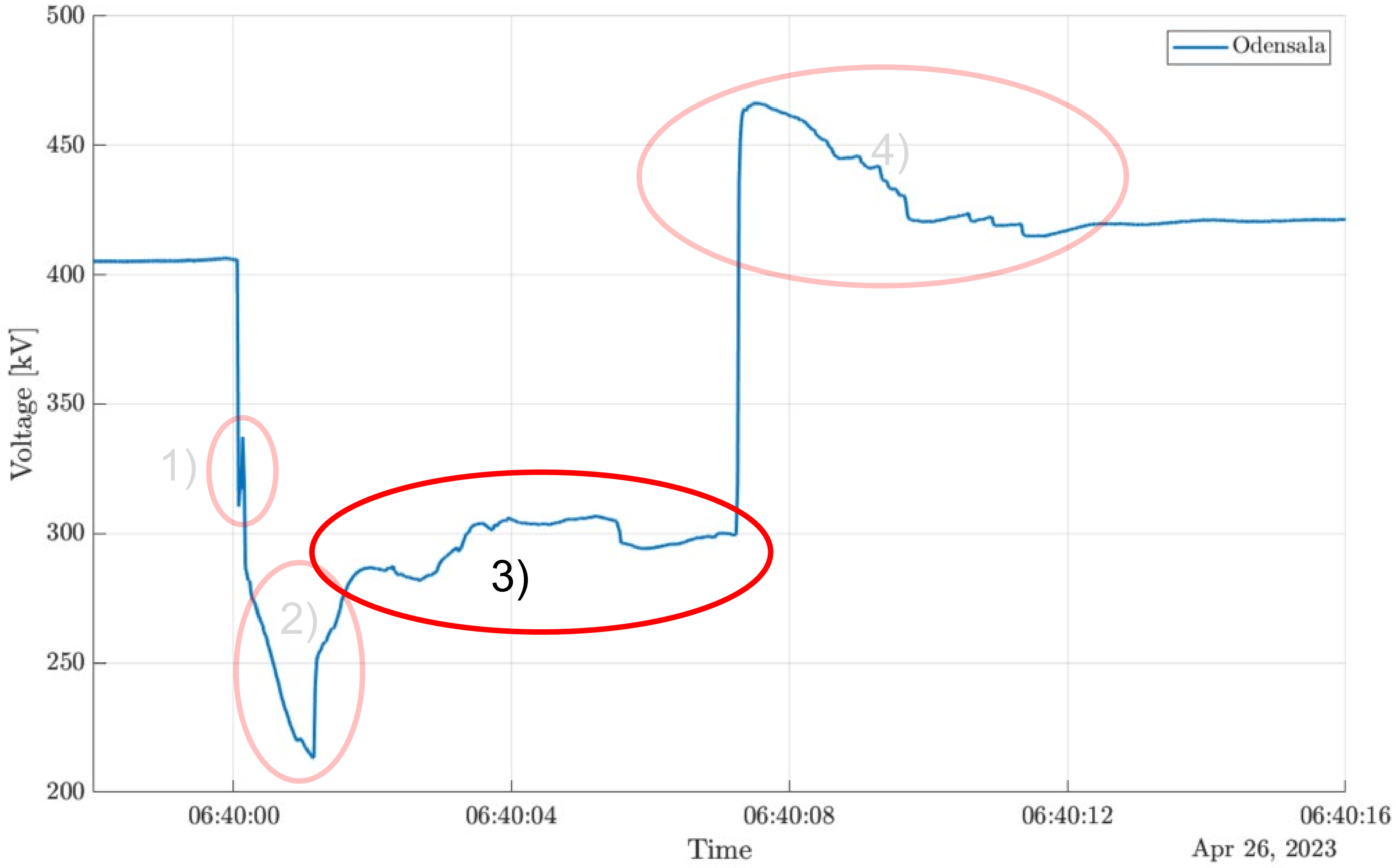


Phase 3: Reactive power support and emergency protection (1)

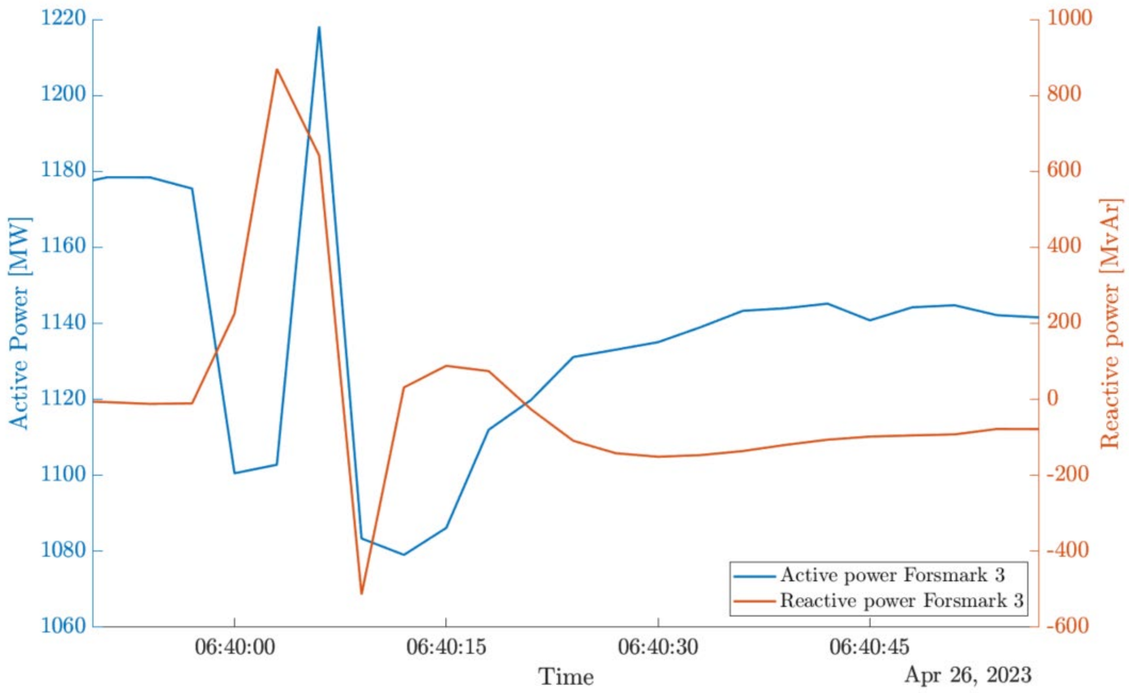
Automatic (extreme) voltage control

> Reactive shunts that connects/disconnects after a few seconds to support the system with reactive power

> A total of 25 connections take place during the 7 seconds fault clearing time

Generators reactive power support

> Generators magnetization systems contributed with significant amounts of reactive power support



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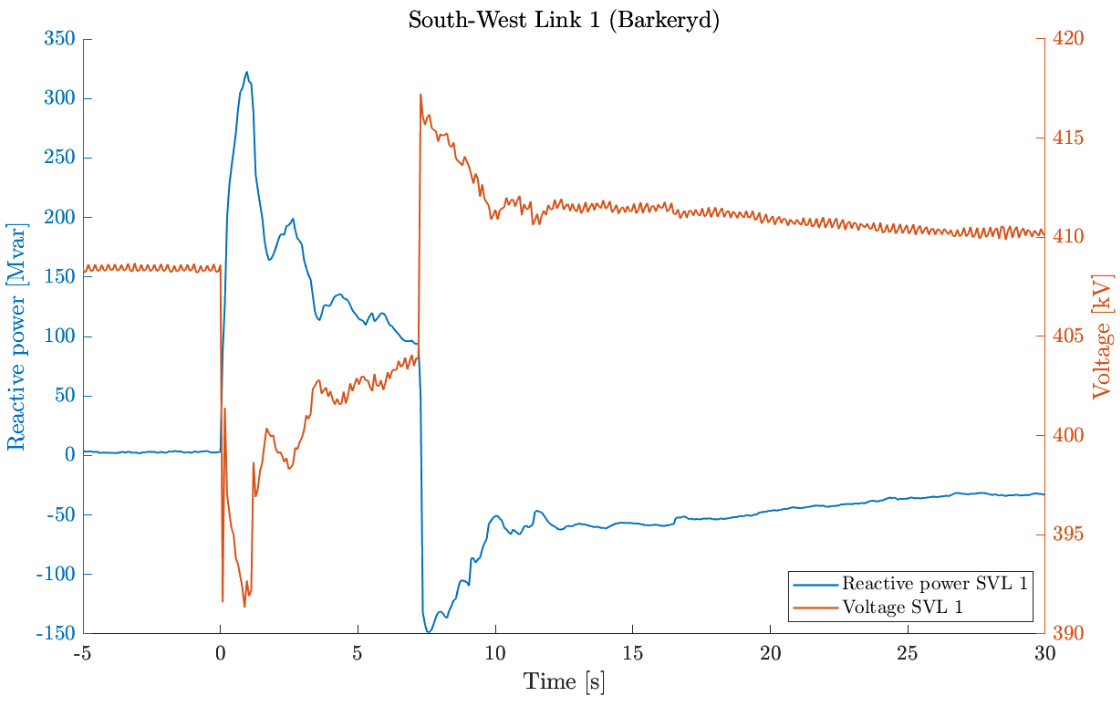
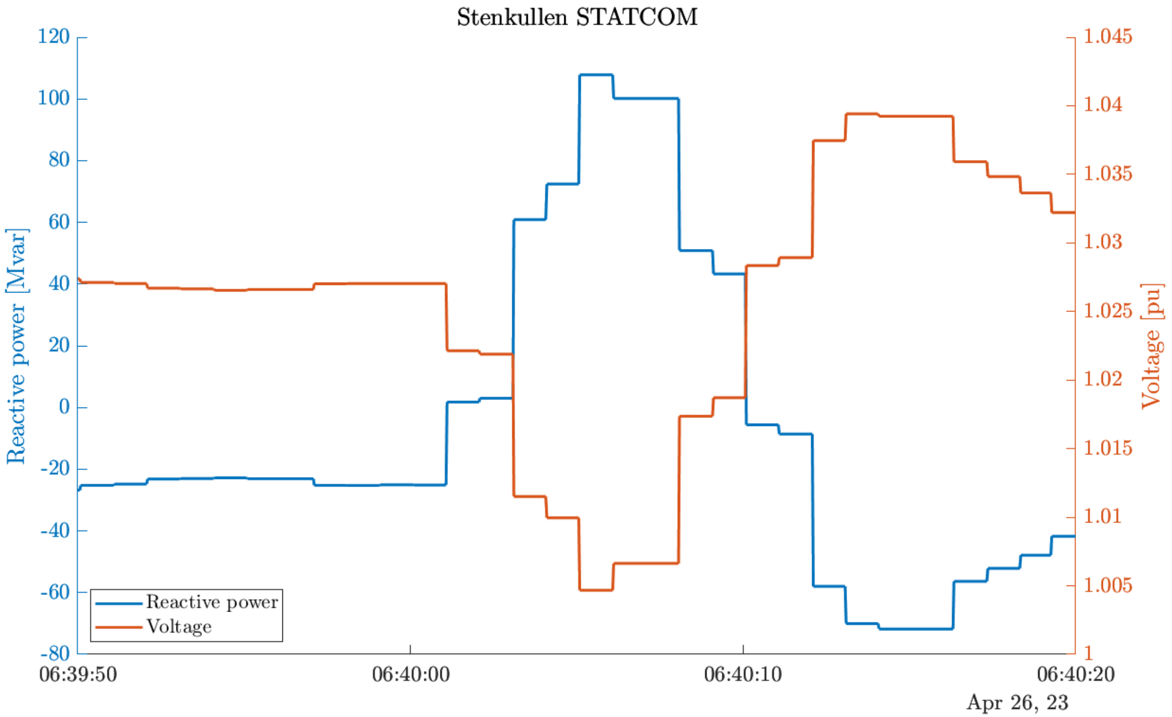
Phase 3: Reactive power support and emergency protection (2)



Disturbance recordings



Trend data

Analysis of the post-fault events

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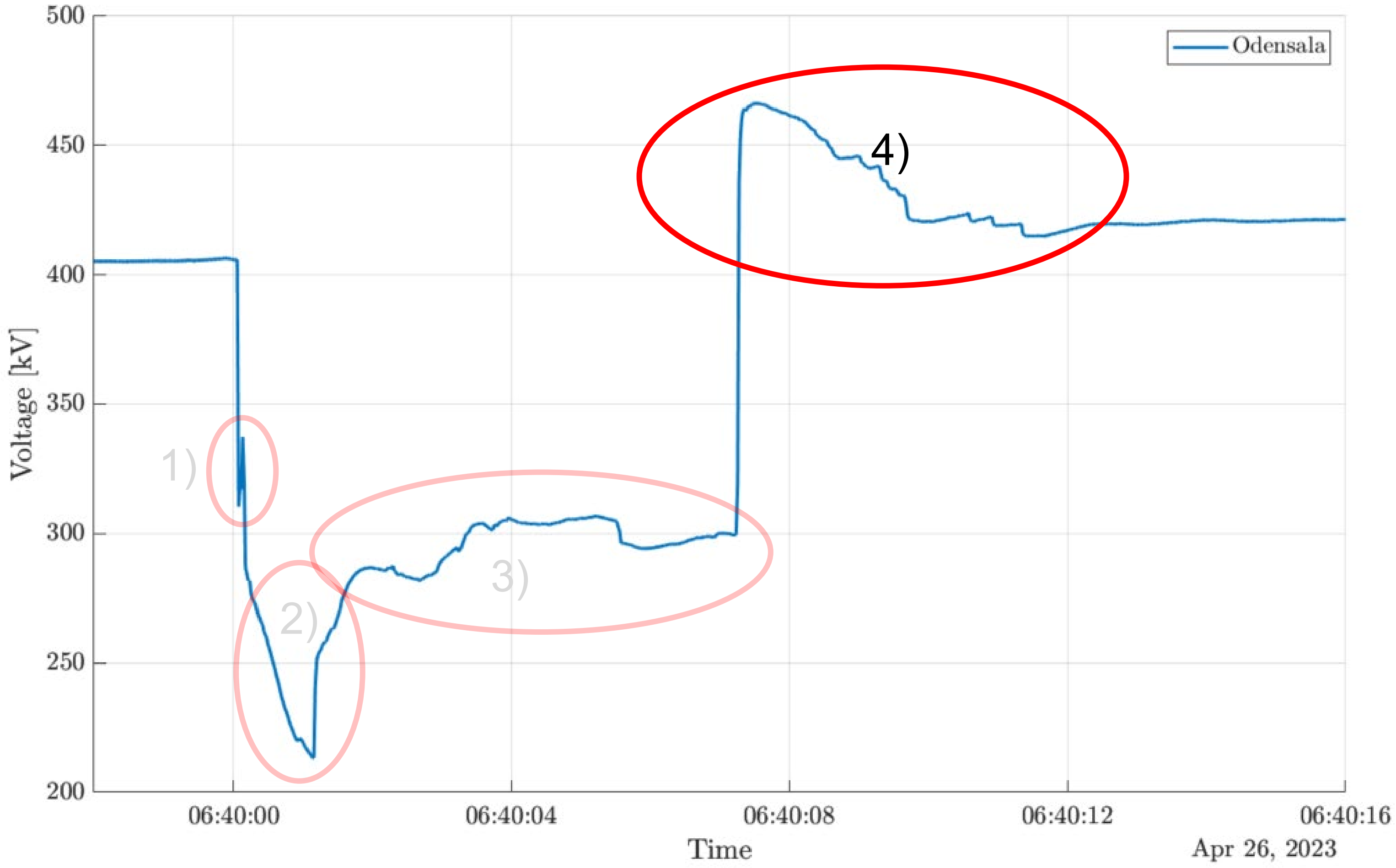
Phase 3: Reactive power support and emergency protection

Phase 4: Fault-clearing and post-voltages



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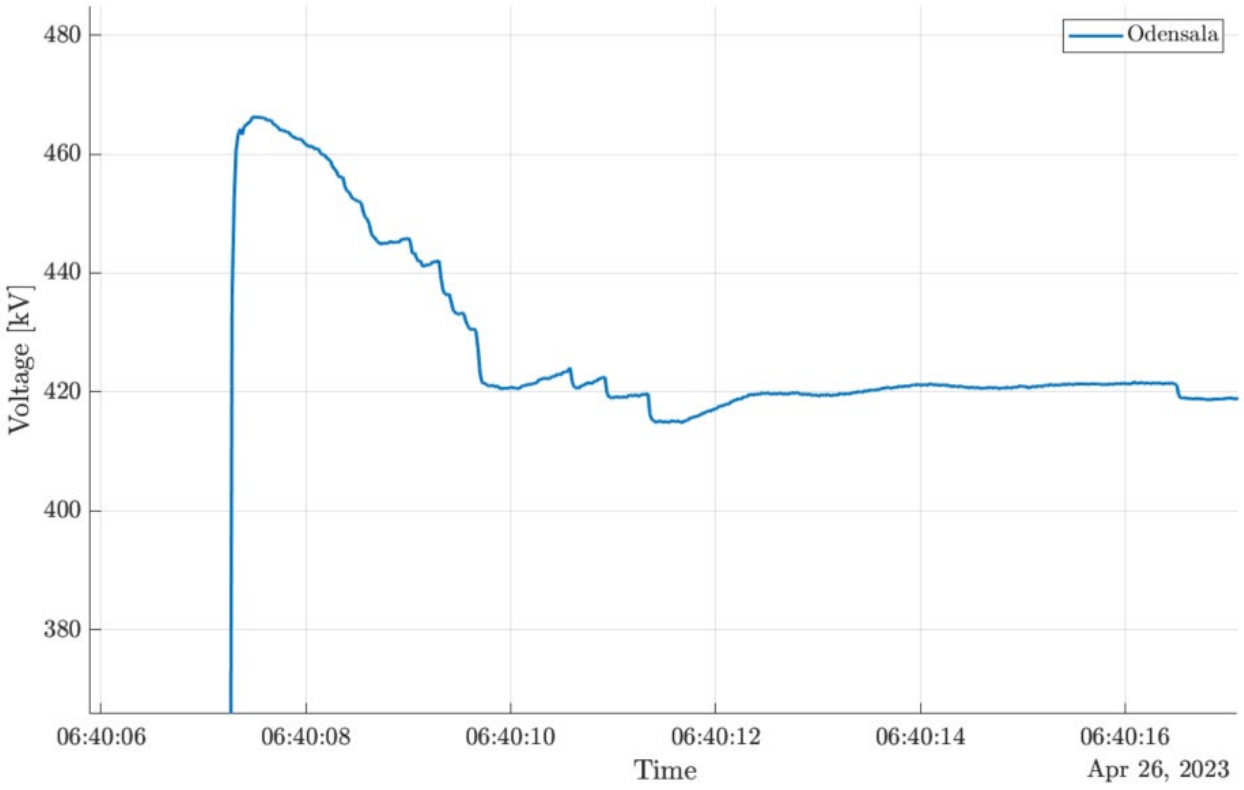
Phase 4: Fault-clearing and post-voltages



Very high voltages once fault was cleared

> Caused by the significant share of reactive components connected during fault and reactive power support of generators/FACTS/HVDC

> High voltages -> risk that overvoltage protection triggers and further loss of generation capacity

> Currently no high-voltage ride through (HVRT) requirements in the national or European grid codes

> In future grid codes, such HVRT will be included to handle these types of events

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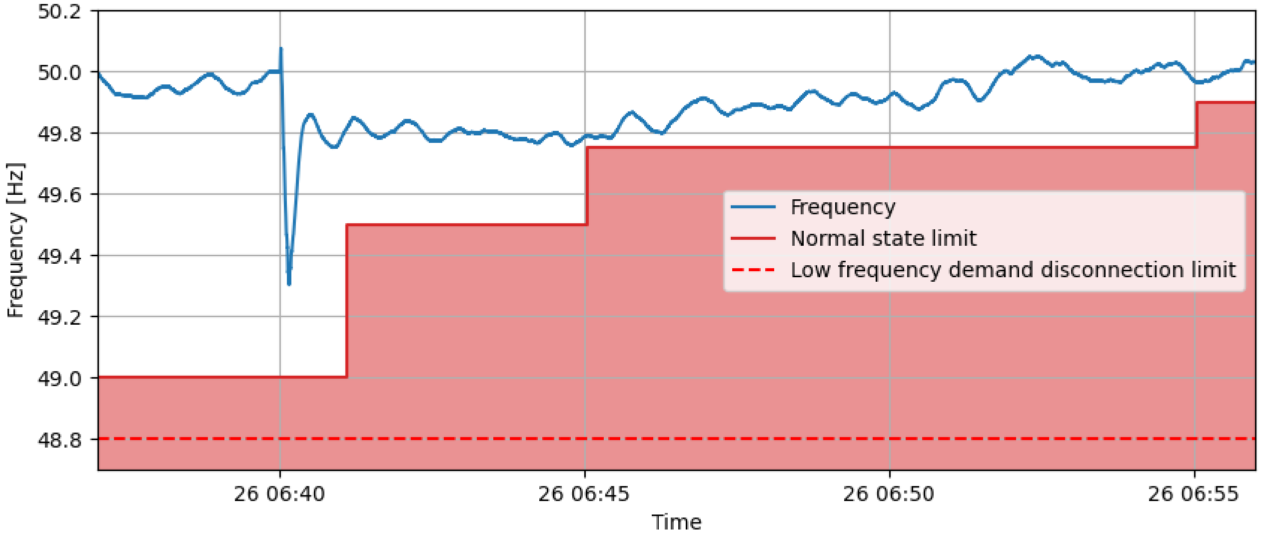
Frequency deviation (1)

The margin to low frequency demand disconnection was large

- Before Forsmark 1 and 2 were disconnected they generated approximately 2100 MW
- The minimum frequency measured was 49,3 Hz
- System inertia was 191 GWs, relatively high for the nordic synchronous area



Frequency containment and restoration

Initial frequency drop was reduced by:

> FCR-D up: 1 450 MW

> EPC: 600 MW

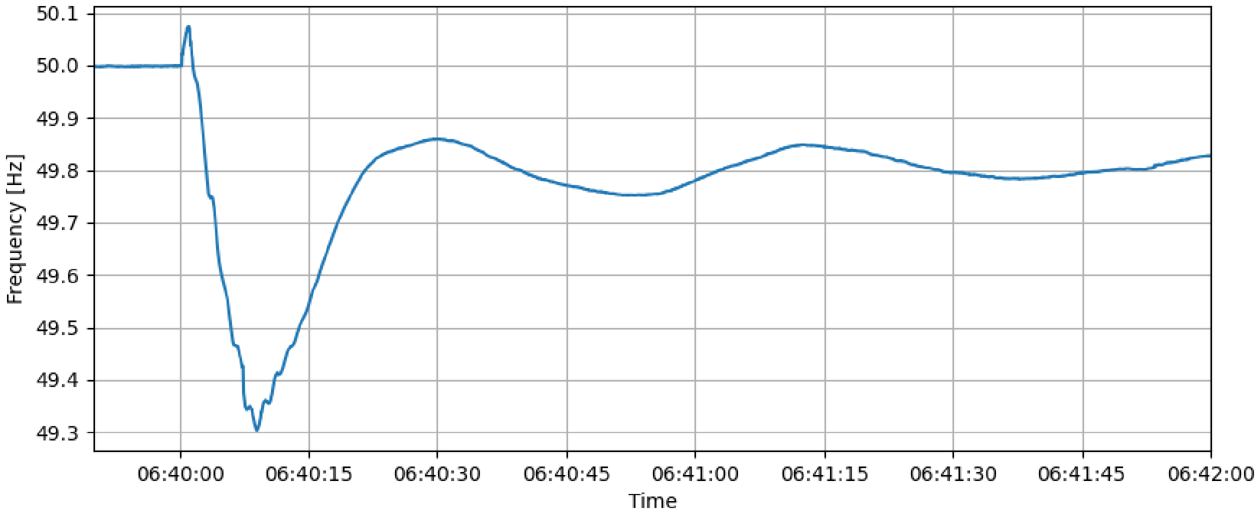
> Frequency and voltage dependent load

> No FFR was procured due to the high inertia

Disturbance reserve and FRR was activated to restore the frequency to the normal operation range (49,9 – 50,1 Hz)

> Disturbance reserve: 700 MW (gas turbines)

> mFRR: 2 431 MW in the Nordics



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Frequency deviation (2)

System behavior can be replicated through simulations

> The Nordic TSOs have a model that can simulate the frequency deviation if given the pre-disturbance state as well as the specifications of the incident

> The model has only been trained on N-1 incidents but, despite this, managed to replicate the frequency minimum of the Hagby incident quite well

> The measured data for frequency minimum differed only 0,0033 Hz from the simulated

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Frequency deviation (3)

The simulations show that on April 26th there were good margins for dealing with a large disturbance

> Additional simulations with this model indicates that the margins in the system were such that it is unlikely load shedding would have been activated even if some of the EPC had not been available or if the inertia had been lower

> The model indicates that even a disconnection of Forsmark G3 may not have resulted in load shedding – however, the model is not trained to replicate incidents of that magnitude so we cannot say for certain

Conclusions

A very unusual event with a *very* long fault-clearing time

> Further analysis whether our protection systems can be enhanced with higher redundancy

> The importance of emergency protection systems was vital for the system stability during the fault

”Good” measurement data is a key for the analysis of faults

> Fast access to disturbance recordings and/or phasor measurements

Events like these provides us with input and knowledge about the power system’s behavior and weaknesses

> An opportunity for validating our models

> Insights in requirements for emergency protection systems and development of grid codes