Case no: Svk 2023/1561 **Datum:** 2023-05-09

The disruption on April 26, 2023

Description of the sequence of events of the disturbance

SVENSKA KRAFTNÄT

Swedish power grid

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Content

Summary

This report describes the sequence of events of the operational disruption.

Wednesday morning, April 26, at At 06.40 a very serious malfunction occurred in the Swedish transmission network. The primary cause was a fault in connection with connections for electrical work at station Hagby, north of Stockholm. The automatic protective equipment in the station did not function properly due to two independent faults in the control system.

During the fault, the operating voltage became very low in large parts of the transmission and distribution networks and the surrounding area. The Stockholm region

The low operating voltage lasted for seven seconds and caused disturbances in the Stockholm region's electricity supply and in important social functions, e.g. rail-based public transport, traffic lights, traffic routes, radio and TV broadcasts.
No physical injuries occurred.

During the disruption, the voltages were so low that the system was in emergency mode. The voltages were also outside the required voltage profile for Forsmark FT46, which meant that the disturbance was not covered by the requirements for immunity to short circuits and voltage variations. As a result, Forsmark 1 and 2 were automatically disconnected, the fault disconnection seems reasonable. Other power production was also disconnected as a result of the low voltages, e.g.

Host KVV8.

The loss of production resulted in a frequency deviation of 49.3 Hz.
The frequency deviation triggered activation of the frequency restoration reserves as well as the EPC. The frequency was restored using the frequency restoration reserve and the disturbance reserve. The power system was in normal operation with respect to frequency throughout the course. Disruptions in the electricity supply were caused by very low operating voltages, the frequency disturbance is deemed not to have caused any disturbances in the electricity supply.

1 Introduction

During Wednesday morning, April 26, at 06.40, a very serious disruption occurred due to several interdependent and independent failures.
The disruption was primarily caused by a fault in connection with connections for electrical work in Hagby, north of Stockholm. The fault gave rise to very low voltages in large parts of the Mälardal region. The low voltages remained for seven seconds and caused several subsequent disturbances, one of which was an automatic disconnection of Forsmark 1 and 2 from the transmission network.

In this report, Svenska kraftnät describes the course of events at station Hagby that caused the disturbance and also describes the consequent effects from the low voltages. The report also describes the subsequent frequency disturbance. Finally, the identified deficiencies that Svenska kraftnät has identified in connection with this initial investigation are described.

2. The operating mode before the disturbance

Below is described the operating mode in the power system before the malfunction in station Hagby occurred.

2.1 Works in the network

On the morning of April 26, a number of works were in progress in the transmission system, which meant that network components in Table 1 were scheduled to be out of service in southern Sweden.

Table 1. Relevant network components that were planned out of service in the transmission system before the disturbance occurred.

The works	Comment
Ekhyddan-Alvesta	The work for the new 400 kV station Hageskruv
Hallsberg-Timmersdala The stone hill	Preparatory work for renewal of the 400 kV station Timmersdala
Högdalen-Skanstull	Out of service in connection with Ellevio's project work
Djurmo EK4	Bypassed in connection with maintenance
Support EK1	Bypassed to regulate the voltage in Stornorrforsen (after previous failure on X1). For the same reason, the Easter drive in Hjälta was in operation.
Hagby	Hagby T2, one of the 220 kV lines Hagby-Järva, the 220 kV lines Hagby-Vallentuna and Hagby-Måby were planned to be disconnected in connection with the work in Hagby.
Hallsberg	Maintenance was underway on a busbar section in Hallsberg

2.2 Flows in the network

Before the disturbance occurred, transmission was moderate to/from electrical area SE3 (see Table 2). Section 2 and Section 4 utilized approx. 60% of allocated commercial capacity, which gave approx. 2,000 MW margin against the dimensioning N–1 error that the commercial capacity for those sections had been allocated based on. The transmission system was thus in normal operating condition. See Figure 1 for an overview of the flow pattern before the disturbance.

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Table 2. Utilization of average flows to/from SE3 relative to allocated trade capacity Total Transfer Capaciy (TTC).

Cut	Trading capacity TTC [MW]	Utilization [%]	Comment
SE2 > SE3	6 300	62	About 2400 MW marginal
SE3 > SE4	4 300	60	About 1740 MW marginal
SE3 > NO1	2 141	49	About 1100 MW marginal
DK1 > SE3	600	90	About 60 MW marginal
SE3 > SE3LS	546	92	About 45 MW marginal
SE3 > F.I	1 200	1	About 1189 MW marginal

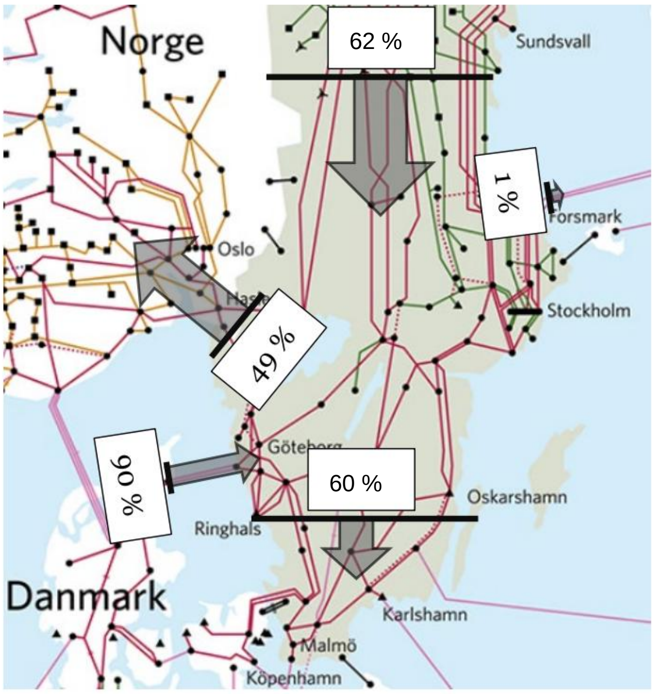

Figure 1. Overview of the flows to/from electricity area SE3 before the disturbance.

2.3 The production mode in the network

In total, the Swedish power system produced approx. 17.0 GW, had a total consumption of approx. 14.6 GW and exported approx. 2.7 GW before the disruption occurred. Hydropower made up approx. 44% of total production, nuclear power approx. 32 %

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and wind power approx. 16%. Figure 2 shows the reported electricity production before the disturbance.1

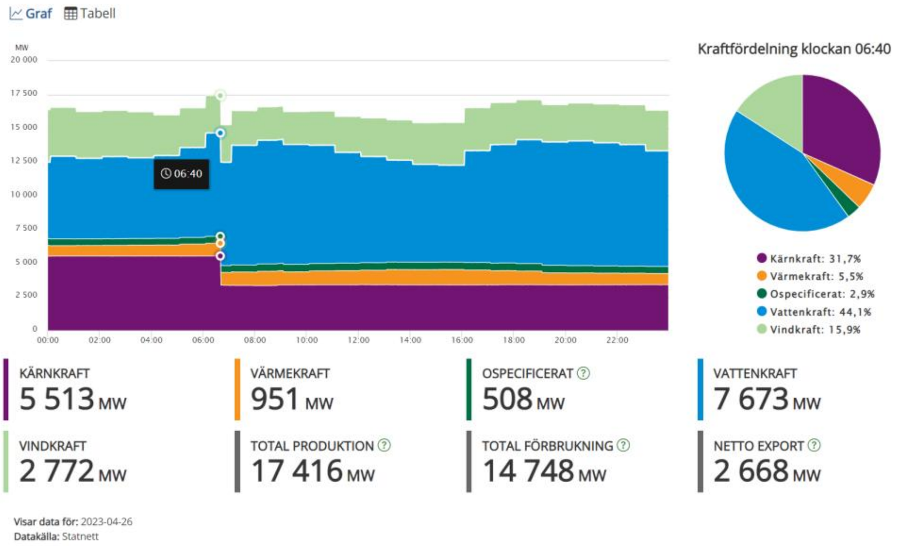

Figure 2. Shows the state of production according to the control room page on April 26, 2023 just before the disruption.

2.4 Comment on the operating mode before disturbance

The operating situation on the morning of April 26 was characterized by good margins to assigned trading capacities and thus to the dimensioned N–1 error. With the margins that existed at the time in question, the conditions in the power system were good to be able to handle a larger error case than the dimensioning N–1 error. Without these margins, the power system would have had completely different conditions to be able to handle major failures. The operating situation was thus favorable for the event that later occurred.

[1] **Figure 2** is taken from the Control Room | Swedish power grid (svk.se). The figure shows the production situation just before the disruption. The reason why the corresponding image just after the disturbance is omitted is that this is not representative on the page because all the data is not updated synchronously. It is only around 08:00 as the data on the page reflects the actual state of production (when primarily hydro and exports have changed to cover the loss of nuclear generation).

3. The course of events

In connection with the planned maintenance work in the switchgear in Hagby, a 220 kV disconnector with continuous operating current was opened. Disconnectors are not made for this and an arc occurred. This resulted in a fault current in two phases which later develops into a fault current in all three phases. Forsmark 1 and 2 were disconnected from the 400 kV grid due to undervoltage after approx. 1 second, shortly after that the generator breakers are disconnected. The primary fault in Hagby is only disconnected after about 7 seconds, which leads to very low operating voltages in the transmission and distribution networks in the region during the fault period. A more detailed description of the course of events follows.

3.1 Connections

In the case of planned connections for electrical works A and B according to operating order Svk no. 242/2023, conditions were specified in points 1-4. Connections under the direction of the Electrical Operations Manager starting with point 5. In point 13, disconnector RL23-AF in CT65 Hagby was to be opened by remote control, which did not work. Remote operation did not work because the interlock logic in the station incorrectly indicated that the X1-A220-F was in the intermediate position. The X1-A220-F was in a compartment that had been demolished and was therefore not visible in the SCADA system. This meant that the disconnector blocking needed to be released to allow the disconnector to operate. The fact that X1-A220-F was in the intermediate position was not known to the electrical operator or switch assistant. Therefore, disconnector blocking for CT65 Hagby was canceled and disconnector opening connections continued through point 16. In point 17, disconnector T2-220-F1 in CT65 Hagby was to be opened but instead T1-220-F1 in CT65 Hagby was operated, then this was opened with operating current whereby a two-phase short circuit L1-L2 via electric arc occurred which then turned into a fault current in all three phases. Figure 3 illustrates where in the 220 kV switchgear in Hagby the fault occurred.

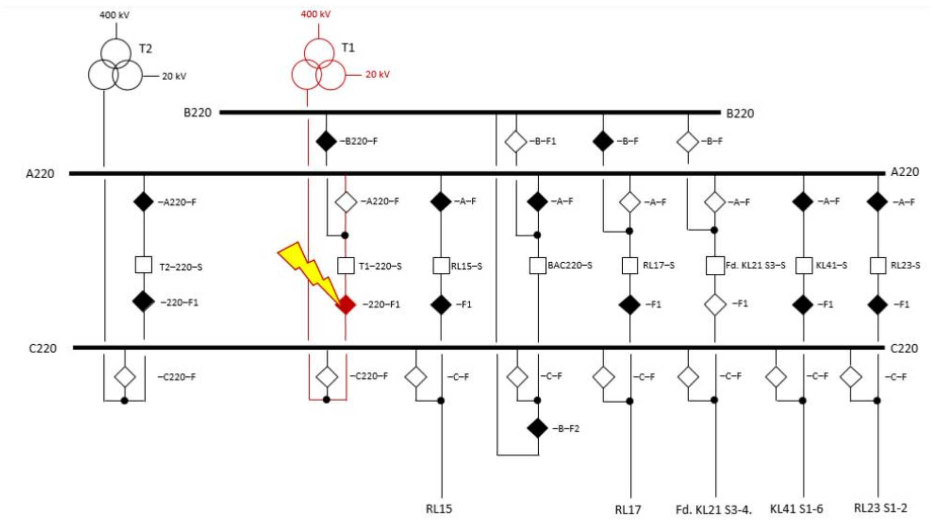

Figure 3. The commissioning diagram for the 220 kV switchgear in Hagby where the short circuit that occurred at the connections is marked with a flash.

3.2 Upside coupling

The protective equipment in the CT65 Hagby is designed to comply with the single fault criterion. At 220 kV there are redundant busbar protection and circuit breaker fault protection. Before the primary fault, there was a known fault in 2 of the 3 phase busbar protection Sub 1. Replacement of the protection is already planned and the known deficiency has not affected the fault disconnection at the primary fault in Hagby.

The short circuit meant that both 220 kV busbar protectors tripped momentarily in CT65 Hagby and tripped all 220 kV circuit breakers. This is correct because the busbar protectors are measuring on T1-220-IT, which sits in T1's bushing, which meant the fault was in the measuring zone. However, the fault was not disconnected when the T1-220-S was switched off because there was still a fault current input from the 400 kV mains through the T1's 400 kV compartment. Due to two independent failures in the control system, the T1-400-FS did not disconnect until approximately 7 seconds later. Troubleshooting in Hagby after the disturbance has revealed a design flaw in the protection system of Sub 1 as well as a fault in the tripping circuit of Sub 2, which may explain the initial failure to trip the T1-400-FS. The primary fault was disconnected by T1's zero voltage automatic.

Forsmark 1 and 2 were disconnected from the 400 kV network after approx. 1 second after the short circuit due to the long-term voltage dip caused by the fault, this is described in more detail in chapter 4.2. There has also been a tripping of FT41 Kolbotten FL4-S due to abnormally high asymmetry currents in combination with high phase currents due to the disturbance. The switch in the FT41 Kolbotten was switched on again by the operation recovery automatic (DUBA) after just over 1 minute.

4. Consequences for the power system

The primary fault in station Hagby gave rise to very low voltages. This caused disturbances in the Stockholm region's electricity supply and important social functions, e.g. rail-based public transport, traffic lights, traffic routes, radio and TV broadcasts. No physical injuries occurred.

In connection with the operational disruption, a number of larger production facilities were also disconnected from the transmission network, including Forsmark 1 and 2. Before the disturbance occurred, Forsmark 1 and 2 together had a production of approx. 2,130 MW. Additional power generation may also have been disconnected in regional grids. The loss of production was thus at least 2,130 MW, which is significantly greater than the dimensioning N–1 error, which at the time of the disturbance was 1,400 MW. The frequency dropped to 49.3 Hz but recovered relatively quickly.

Below follows a more detailed account of the consequences that arose in connection with the operational disruption, management of the frequency deviation and analysis of the system parameters voltage and frequency.

4.1 Voltage levels in the electrical vicinity

High fault currents during the operational disruption in Hagby contributed to a sharp voltage drop in the electrical vicinity. Due to the extent of the error, a clear impact on other more distant stations could also be identified. Figure 4 shows the voltage development during the sequence of events for some nearby stations. The fault current lasted for about 7 seconds until the fault could be completely disconnected. After disconnection of the fault, the voltage increased sharply, up to about 465 kV, for a number of seconds before magnetizing systems of remaining generating facilities were able to restore the voltage to a level closer to the normal voltage range.

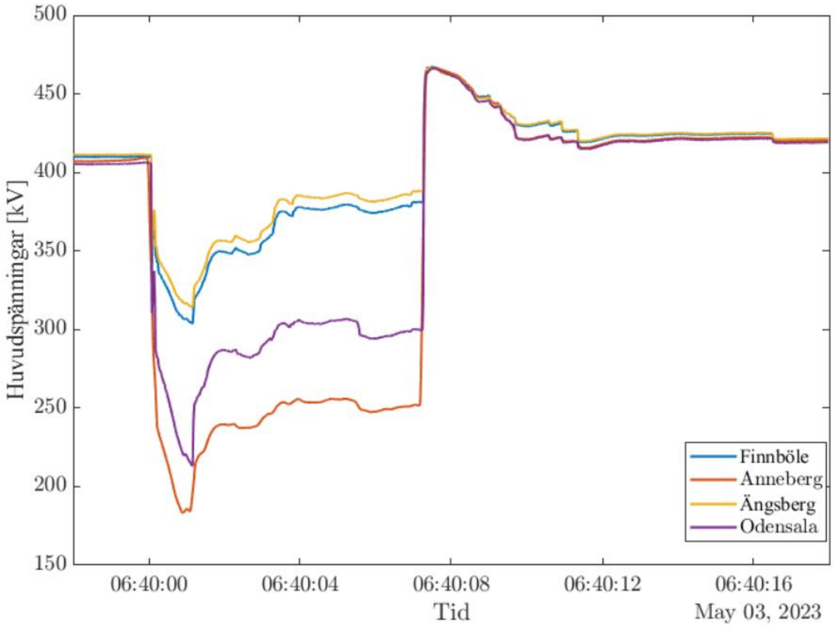

Figure 4. Measured main voltages (positive sequence) in stations in the electrical vicinity of Hagby.

High-resolution voltage measurements during *the entire* disturbance sequence are missing for the stations Forsmark FT46 and Forsmark FT47, but by analyzing measurement values from the ALBA/energy meter system2, an approximate picture of the voltages during the sequence of events is obtained, which is shown in Figure 5. Preliminary analyzes of the data from the disturbance recorders show, however, that the voltage increase after the fault disconnection probably was significantly higher, closer to 470 kV, than shown in Figure 5.

2 ALBA data is collected from energy meters that have a measurement resolution of 3 seconds.

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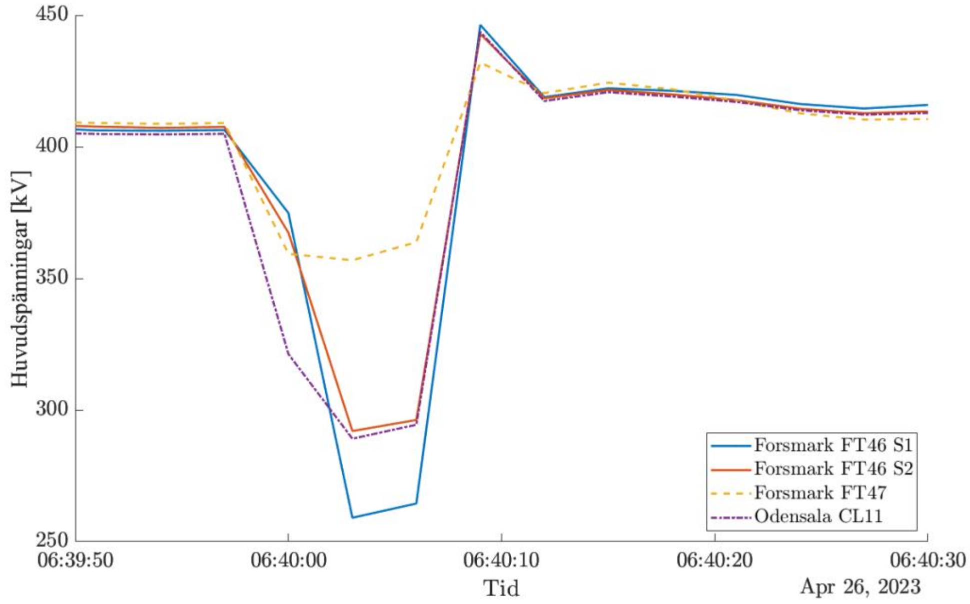

Figure 5. Principal stresses in Forsmark FT46 S1/S2, Forsmark FT47 (as well as Odensala as a reference) with measurements from the ALBA system.

Figure 6 shows the active and reactive power output from Forsmark 3 during, and a few seconds after, the operational disruption in Hagby. As high-resolution data is missing for stations Forsmark FT46 and Forsmark FT47, ALBA data is used and despite a relatively low time resolution, the production of reactive power during the fault, as well as the consumption of reactive power after the fault has been disconnected, can still be clearly observed. During the outage, the reactive power generator contributed up to 870 Mvar to the grid, which supported the system voltage. After the fault in Hagby had been disconnected, the voltage was momentarily raised in the grid, causing the magnetizing system to instead work to lower the voltage. The generator then consumed reactive power down to 500 Mvar whereupon a few seconds later it returned to a similar level as before the malfunction.

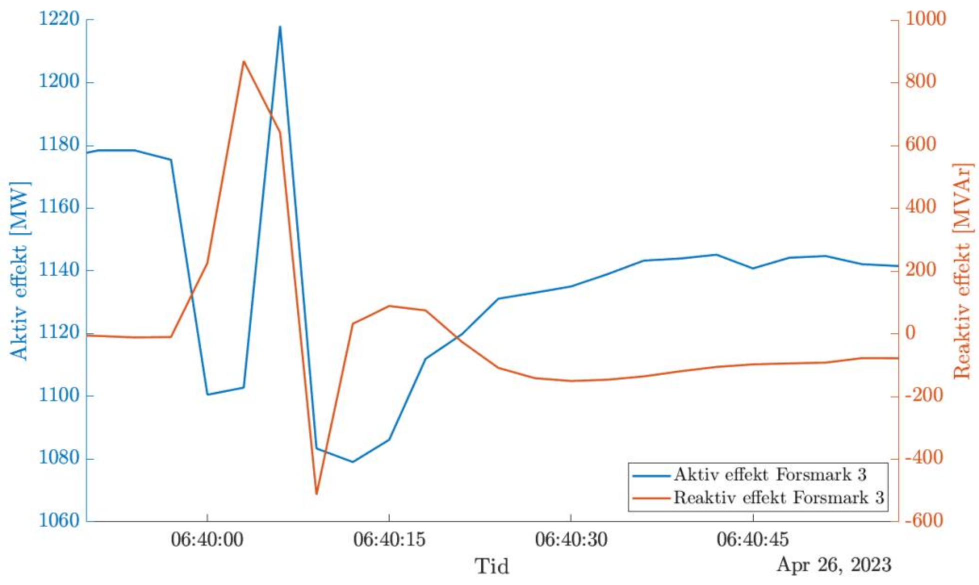

Figure 6. Active and reactive power in Forsmark 3 during the operational disruption.

Due to the greatly varying voltages, a greater number of automatic disconnections and connections of shunt reactors and shunt capacitors took place.
In connection with the malfunction, a total of 25 disconnections and connections of shunt reactors and shunt capacitors connected to either the 400 or 220 kV grids took place during a time interval of about 5 seconds, where all contributed to raising the voltage in the system. The large voltage increase that occurred after the fault in Hagby was disconnected can thus be largely explained by the large amount of reactive components that were connected during the fault event.

After the fault was disconnected and within 8 seconds, another 35 disconnections and connections were performed; where most contributed to lowering the tensions in the system. In addition to the contribution from these components, there is also reactive support from reactive components in distribution networks.

4.2 Disconnection of Forsmark 1 and 2 in FT46

According to fault recorder files from the time of the fault, the system voltages on the busbars in FT46 were low before the fault disconnections. Analysis of data from disturbance recorders shows that the voltage on the busbars in FT46 went outside the required voltage profile, according to ch. 3. § 5 of SvkFS2005:2. The low voltages that occurred are outside the requirements regarding immunity to short circuits and voltage variations. The fault disconnection is therefore considered reasonable in view of the voltage's low magnitude and duration.

4.3 Analysis and impact on Forsmark 3

Forsmark 3 was able, despite a major impact on the system voltage in the station in question, to maintain its connection to the grid. High-resolution measurements are missing in the station, which is why ALBA data has been used to analyze the course of the disturbance. In Figure 7, the voltages in the stations Forsmark FT46 S1/S2 and Forsmark FT47 are shown together with the requirements for resistance to disturbances with respect to voltage levels over time (LVRT) according to SvkFS 2005:2. It is established that the voltages in the Forsmark FT47 were *very close to* the required voltage profile for the plant to be kept connected to the grid. In Figure 7, it can also be read that the measured voltages in Forsmark FT46 S1/S2 are significantly below the voltages that are required for interference resistance in SvkFS 2005:2.

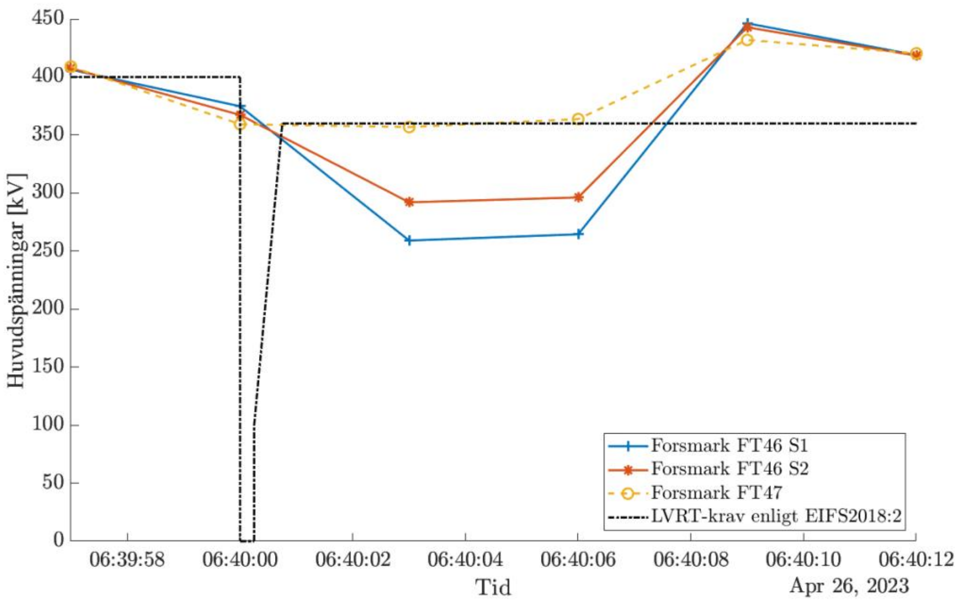

Figure 7. Voltages in Forsmark FT46 S1/S2 and Forsmark FT47 and LVRT requirements according to SvkFS 2005:2.

By correlating and recalculating voltages from PMU measurement in Odensala against ALBA data from Forsmark FT46 S1/S2 and Forsmark FT47, an estimate of how the voltages in these stations looked during the disruption can be estimated, which is shown in Figure 8. The figure shows that the voltage levels for the Forsmark FT47 may have been *below* the interference tolerance requirements for 2 seconds after the fault occurred. However, these results are associated with uncertainty

due to the resolution of the measurement data.

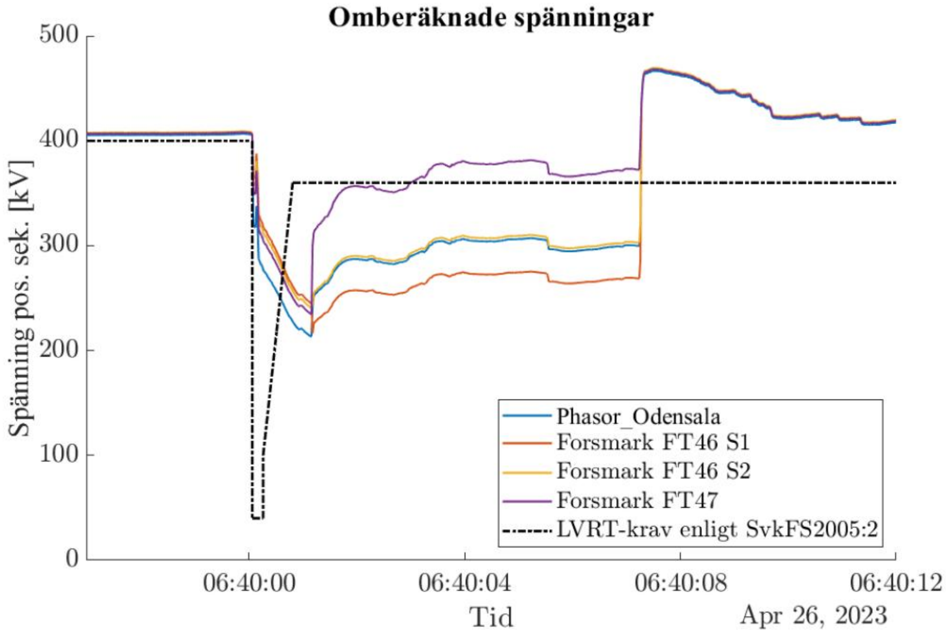

Figure 8. Recalculated and estimated voltages (positive sequence) Forsmark FT46 S1/S2 and Forsmark FT47 and LVRT requirements according to SvkFS 2005:2.

The relatively large difference in voltage levels between the stations Forsmark FT46 S1/S2 and Forsmark FT47 was due to the current network topology.

4.4 Loss of other production

Through analysis of ALBA measurement data and estimates from the SCADA3 system, other production facilities that were disconnected during the disruption could also be identified. The applicable production plants, their location in the respective electricity area, type of production plant, as well as outages and maximum active power are presented in Table 3. It is possible that more production plants may have been affected and further investigations will be carried out to investigate what caused the disconnections. It should also be mentioned that there is some uncertainty regarding the accuracy of the estimates and any loss of production needs to be further confirmed via the SCADA system of the transmission network or connected distribution network.

[3] Supervisory Control and Data Acquisition (SCADA) constitutes the functions that include data collection, control and remote monitoring of the Swedish main network.

Table 3. Other production facilities that were affected by the disruption.

Production facility	Electricity area	Type of production facility	Loss of active effect	Maximal active effect
The host agency KVV8	SE3	Cogeneration plant	77 MW*	~140 MW
Untra power plant	SE3	Hydroelectric plant	39 MW**	~43 MW
Älvkarleby power plant	SE3	Hydroelectric plant	38 MW (out of a total of 80 MW)*	~125 MW
Finnfors power station	SE1	Hydroelectric plant	18 MW*	~44 MW (estimate)

* Only controlled via SCADA data. **Verified via ALBA data.

Figure 9 shows the active effect during and a couple of hours after the operational disruption in Hagby for a number of production plants where measurement data from the ALBA system was available. A major impact can be identified on the Untra power plant, which was completely disconnected from the grid for a number of minutes. A gradual reconnection to the network can then be seen during the following 30 minutes. Production, which is geographically and electrically weakly connected to the station in Hagby, was also affected by the disruption. The hydroelectric power plant in Näverede, in SE2, was initially affected by the disruption, but the production level was restored within a couple of minutes.

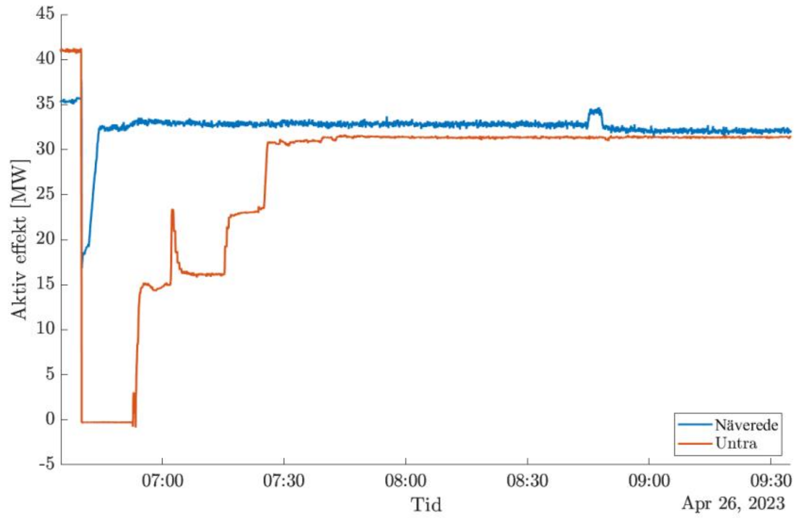

Figure 9. Active power for Nävered's hydropower plant and Untra's power plant.

In the 220 kV station Hallstavik, there is a larger load in the form of Hallsta Paper mill Holmen Paper, partly gas turbines operated by Svenska kraftnät. IN

Figure 10 shows the activation of the gas turbines a few minutes after the malfunction occurred. At the same time, a relatively clear reduction in the load at Hallsta Pappersbruk can be identified, which has probably stabilized the network. The load is then partially recovered after the fault has been disconnected.

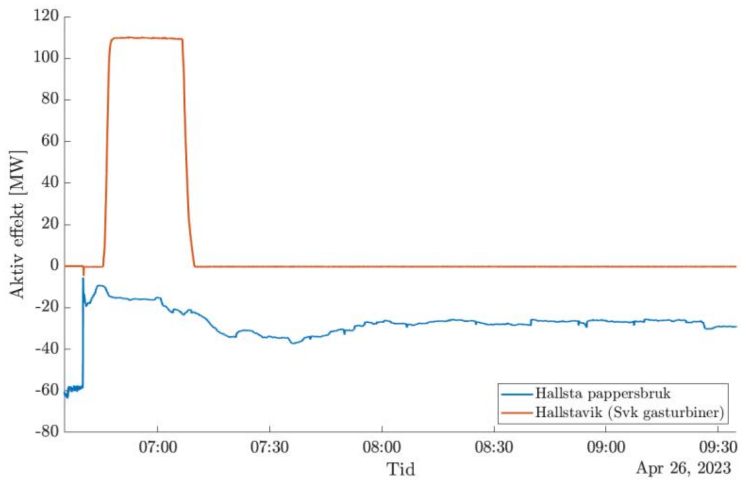

Figure 10. Active power for Hallsta paper mill and Svk gas turbines Hallstavik.

4.5 Frequency deviation when disconnecting Forsmark 1 and 2

From the time the protection tripped the first transformer in Forsmark FT46 until both Forsmark 1 and 2 were disconnected, it took about 0.5 seconds. This meant that a sudden difference between production and consumption arose, which had a direct impact on the frequency in the Nordic synchronous area. Figure 11 illustrates how the frequency dropped quickly in connection with the operational disturbance, the lowest frequency was measured at 49.3 Hz and occurred approx. 8 seconds after the disconnection of Forsmark 1 and 2.

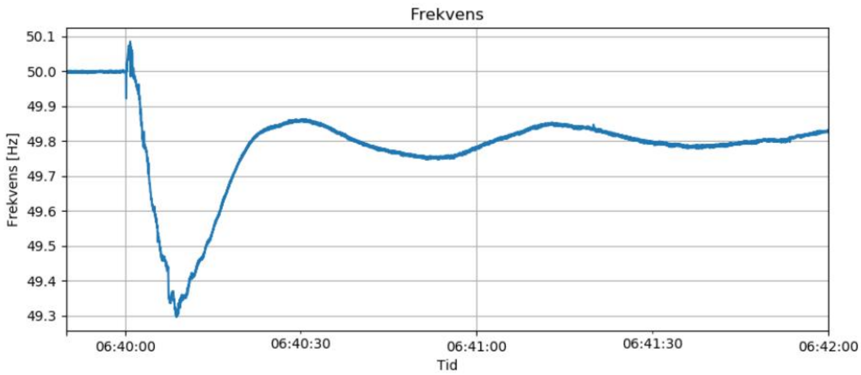

Figure 11. Measured frequency in the Nordic synchronous area in connection with the disturbance on 26 April. The frequency measurement is from station Hallsberg.

Before the protections tripped and Forsmark 1 and 2 were disconnected, they produced a total of 2,130 MW. As can be seen in chapter 4.4, other production was also affected during the disruption, which meant that the total volume of production that was disconnected was probably somewhat higher than 2,130 MW.

The frequency maintenance reserve for disturbed operation upregulation (FCR-D up) is designed to handle disturbances of up to 1,450 MW. A total of 1450 MW FCR-D up and 600 MW frequency holding reserves for normal operation (FCR-N) were available in the Nordic synchronous area when the disturbance occurred.

The low frequency meant that emergency power intervention (EPC) on several direct current connections was activated, in total EPC activated on underfrequency contributed about 600 MW. The disturbance reserve started automatically at underfrequency, all units that were available for underfrequency start were activated, which corresponded to a volume of approx. 500 MW. In addition, approx. 200 MW of the disturbance reserve was also activated manually. In total, the disturbance reserve contributed 700 MW.

Since the minimum frequency was 49.3 Hz, the power system had a good margin for automatic consumption disconnection, AFK. The first stage of AFK is activated if the frequency falls below 48.8 Hz.

Before the disruption occurred, the rotational energy in the synchronous area was 191 GWs, which is an average level of rotational energy seen over an entire year. For the same change in active power, ÿP of the disturbance, the frequency drop will be slower and the frequency deviation will be lower if the rotational energy is high compared to if it is lower. Fast frequency reserve (FFR) is called based on forecasted available rotational energy in the power system. Because the forecast indicated that the amount of rotational energy in the power system would be sufficient, no FFR had been called and the remedial action was therefore not available for activation.

4.5.1 Interaction between voltage and frequency

At the beginning of the disturbance process, when the voltages were very low but before Forsmark 1 and 2 had been disconnected, the frequency increased, see Figure 11. This frequency increase seems to indicate that the consumption was reduced initially due to the low voltage that occurred. Parts of the consumption in the power system are voltage dependent, the consumption decreases when the voltage drops.

The reduction in consumption that resulted from the low voltages resulted in production exceeding consumption, which meant that the frequency increased. When Forsmark 1 and 2 are disconnected, the initial consumption reduction from the low voltages represented a reduction in the resulting fault drop, ÿP for the disturbance. The frequency deviation was therefore probably smaller compared to if the disconnection of Forsmark 1 and 2 had not been caused by low voltage.

4.5.2 Return

After the frequency dip, the frequency remained outside the range of continuous normal operation (49.90-50.10 Hz) for 7 minutes. The frequency stabilized above 49.90 Hz after about 12 minutes, see Figure 12.

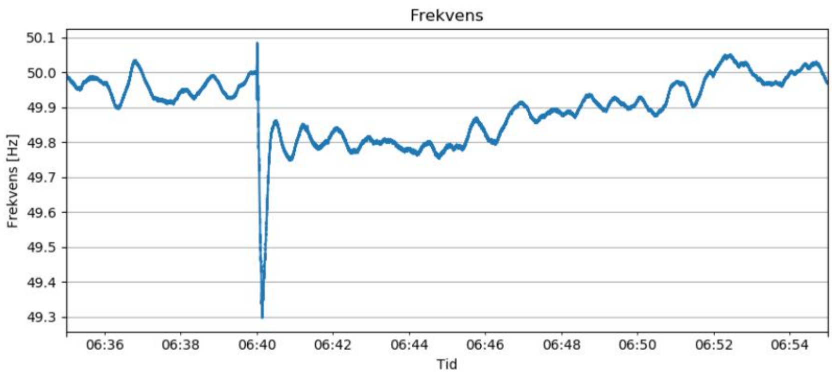

Figure 12. The frequency in the Nordic synchronous area during and after the disruption.

FCR-D up, the disturbance reserve and EPC were successively replaced by manual frequency recovery reserve (mFRR). The deactivation of the EPC started 10 minutes after the disturbance, the EPC on the last direct current connection was deactivated at 07:07. The gas turbines were deactivated after running for about 30 minutes. A total of 2,431 MW mFRR were activated in the Nordics and there were still approx. 7,600 MW mFRR bids left on the bid list.

Forsmark 1 and 2 were not connected on the same day and the balance was corrected in the operating hour with mFRR as well as by the actions of the players on the Intraday market For the hour 07-08 on April 26, the Intraday market had already closed when the disruption occurred and intraday trading could not take place for that hour. The players in the market updated their trading plans for the hours 08-09 and 09-10 which meant that shortly after 9 the trade was in balance and mFRR was deactivated.

5. System operating permit

Table 4 summarizes the system operating conditions for the Swedish power system during the disturbance on April 26. A more detailed description of system operating conditions with respect to voltage and frequency is given in chapters 5.1 and 5.2, respectively.

Table 4. Summary of system operating conditions for voltage, frequency and thermal overload in the Swedish power system during the disturbance on April 26.

Category	System operating permit	Comment
Voltage	Emergency operation	Very low voltages for seven seconds with subsequent interruptions in the electricity supply as a result.
Frequency	Normal operation	Available reserves were sufficient to keep the frequency within the range of normal operation.
Thermal overload	-	Has not been included in the preliminary evaluation.

5.1 System operating condition with regard to voltage

The fault in Hagby caused a severe voltage drop and a voltage increase when the fault was disconnected, in total the power system was in the emergency mode for 9 seconds. The limit value for each operating condition with regard to voltage is shown in Figure 13.

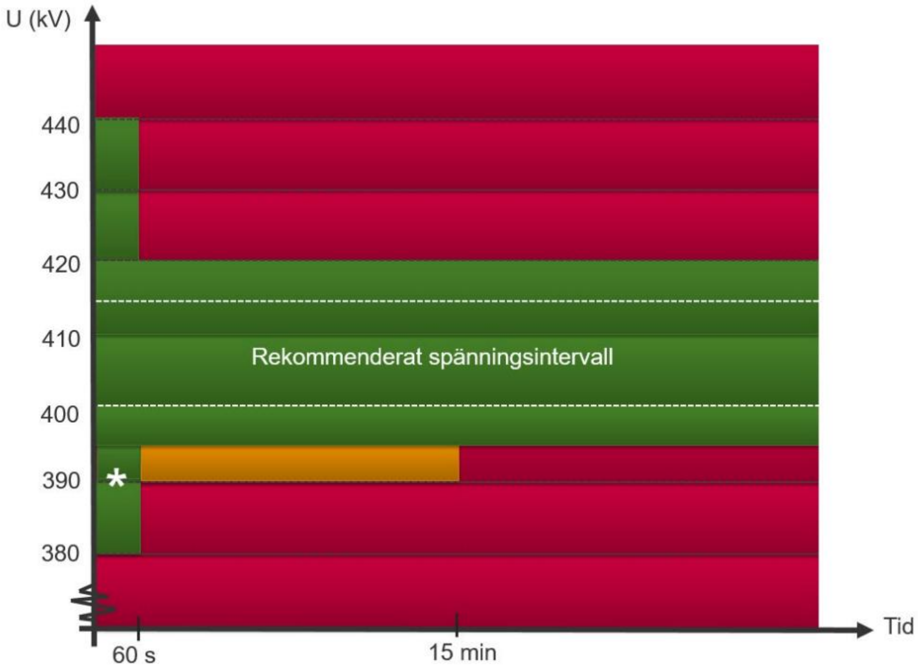

Figure 13. System operating conditions for voltage.

In connection with the failure, a voltage of 183 kV was measured in Anneberg (400 kV), the low voltage lasted for 7 seconds. The lower limit for emergency operation is 380 kV, so the power system was in emergency operation due to low voltages for 7 seconds. The voltages in other stations, see 4.1.

After the disconnection of the fault, the voltage in several stations increased to about 465 kV, the high voltage lasted for 2 seconds. The upper limit for emergency operation is 440 kV, so the system was in emergency operation due to high voltages for 2 seconds.

5.2 System operating conditions with regard to frequency

Throughout the course of the disturbance, the frequency was within the limits of normal operating conditions. Figure 14 illustrates the criteria for the frequency to be in normal, sharpened and emergency operation.

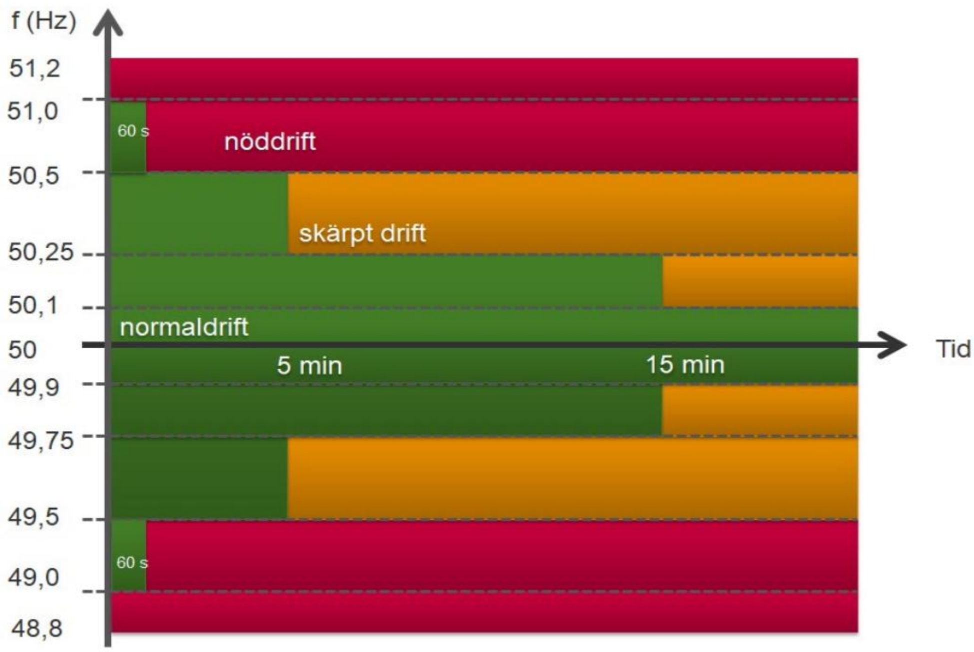

Figure 14. System operating conditions for frequency stability.

In order not to fall outside normal operation, the frequency must be above 49.75 Hz after 5 minutes from the start of the disturbance. Support lines have been drawn in Figure 15 together with the frequency measurement.

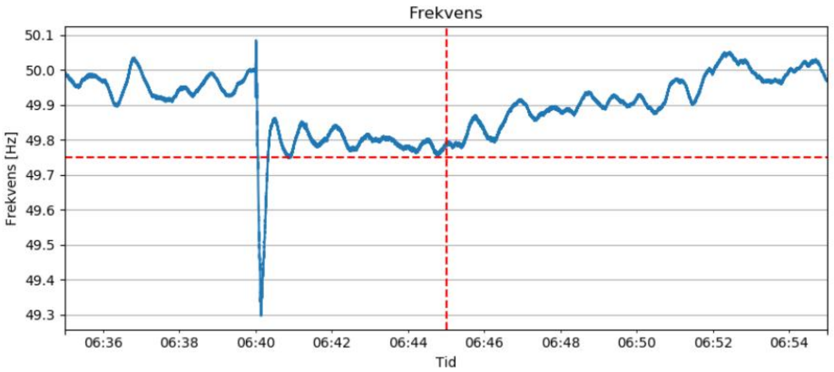

Figure 15. The frequency in the Nordic synchronous area during and after the disturbance on April 26 and support lines in red showing that the frequency was not below 49.75 Hz for more than 5 minutes.

6. Deficiencies noted

The following errors and deficiencies have been identified in connection with the operational disruption on April 26:

1. Disconnectors in Hagby could not be operated remotely because the interlocking logic in the station incorrectly indicates that X1-A220-F is in intermediate position. This means that the isolator blocking needed to be undone to enable operation of the isolator. X1 compartment has already been demolished.

2. Maneuver of faulty disconnector T1-220-F1 was opened with operating current (step from operating orders).

3. 220 kV breaker failure protection Sub 1 should have sent a tripping pulse to T1-400-FS in Hagby but it failed due to a design fault.

4. 220 kV busbar protection Sub 2 should have sent a tripping pulse to T1-400-FS in Hagby but it failed due to a fault in the tripping circuits.

The cancellation of disconnector blocking was a prerequisite for carrying out connections for planned works and is therefore not considered a fault.
Cancellation of disconnector blocking was not regulated in the operating order.

Svenska kraftnät is the system responsible authority, with the task of managing, operating and developing a cost-effective, reliable and environmentally friendly power transmission system in a business-like manner. It includes lines for 400 kV and 220 kV with stations and foreign connections. Svenska kraftnät develops the transmission network and the electricity market to meet society's needs for a safe, sustainable and economical electricity supply. Thus, Svenska kraftnät also has an important role in climate policy.

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