CHARACTERIZATION OF BIG EVENTS SUCH AS TRIPS OF BIG POWER PRODUCING UNITS OR HVDC LINKS

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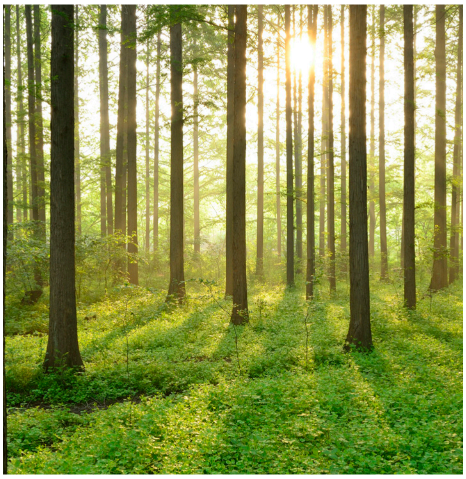

NUCLEAR

GRID INTERFERENCE ON NUCLEAR POWER PLANT OPERATIONS

Energiforsk

Characterization Of Big Events Such as Trips of Big Power Producing Units or HVDC Links

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Foreword

The research and development program GINO aim at gaining better understanding and ability to pro-actively minimize interference on nuclear power plant (NPP) operation due to factors relating to the external grid. The nuclear power plant needs to have stable and reliable grid conditions in operation and during outages.

This project has studied a number of big events, i.e., historical substantial events in the power system and clarify how the nuclear power plants and grid were affected and how they responded to actions to counteract the event. The study investigates critical root causes, such as climate change, that can increase the stressors that ads to the general trend in the generation mix with less inertia and less plannable production.

The report also presents several ways for the nuclear power plants to support the grid.

The survey was carried out by Imtiaz Hoque at DNV. The GINO program is a part of the Energiforsk nuclear portfolio, financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft and Karlstads Energi. GINO has additional funding from SSM and SVK.

These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

Summary

Within the Energiforsk program, GINO, this report describes and characterizes large disturbances, and investigates the importance of the remaining nuclear power units in the Nordic power system, in the light of the ongoing energy transition towards intermittent converter connected generation.

Like all power systems, the Nordics is experiencing significant changes: The proportion of converter connected generation is increasing in the generation mix at the expense of conventional, large synchronous generators; More and more large HVDC connections emerge both within and between power systems and to connect offshore generation; The demand side, including export, is changing and becoming less predictable but possibly more controllable; The energy transition will lead to further electrification and higher utilization of the power system; Grid code requirements are expected to expand and the market-based solutions for ancillary services will be extended in the Nordics; Climate change will lead to more frequent extreme weather conditions that can trigger multiple faults that traditional power systems are not designed to withstand; the digitization of the power system increases its vulnerability to cyber-attacks and new types of human error. Several different factors contribute to the conclusion that the Nordic system will probably be exposed to more stress in the future while the margins in the system are decreasing.

A set of historical events are described and analyzed, and specific attention is paid to triggering events and root causes that are likely to become more significant in the future Nordic system. Other events provide insights into likely courses of events for the Nordic power system. A third category is relevant for the effect on and potential of Nuclear Power Plants (NPPs) during big events.

In the Nordics, there is a potential for the NPPs to support the power system in stressed and unstable situations to a greater extent than they do today. From this point of view, the greatest benefits of NPPs compared to other power generating units, are their sizes, the units being synchronous, their primary energy source being storable and them being located near high load centers. Specific examples of potential contributions could be emergency voltage support systems, providing FCR-N in both directions during normal NPP operation, being reimbursed for providing inertia, providing FCR-D in both directions and staying grid connected as long as possible, diversifying trip levels of NPPs to avoid simultaneous tripping of several large units, installing properly dimensioned and controlled braking resistors to efficiently damp large and reasonably slow oscillations, implementing smart switchgear design, advanced protection and control solutions, and efficient remedial action schemes on a selective and probabilistic basis.

Keywords

Big events, future power system, emergency support, ancillary services, NPPs

Storstörningar, framtidens kraftsystem, störningsreserv, stödtjänser, kärnkraft

Energiforsk

Sammanfattning

Inom Energiforksprogrammet, GINO, beskriver och karakteriserar denna rapport storstörningar, samt undersöker vikten av de i Norden återstående kärnkraftsenheterna mot bakgrund av den pågående energiomställningen till intermittent och omriktarstyrd produktion.

Liksom alla kraftsystem, genomgår det nordiska stora förändringar: andelen omriktarstyr produktion ökar i produktionsmixen på bekostnad av produktion från stora, konventionella synkrongeneratorer; fler och fler stora HVDC-länkar byggs både inom och mellan kraftsystem och för att ansluta havsbaserad produktion; lastsidan, inklusive export, förändras och blir mindre förutsägbar men möjligen mer kontrollerbar; energiomställningel kommer att leda till ökad elektrifiering och högre nyttjandegrad av kraftsystemet; krav i nätkoder förväntas utökas och stödtjänster i Norden kommer att bli mer marknadsstyrda; klimatförändringen kommer att leda till mer frekventa, extrema väderförhållanden vilket kan resultera i multipla fel som traditionella kraftsystem inte är designade för att hantera; digitaliseringen av kraftsystem ökar dess sårbarhet för cyber-attacker och nya typer fel tillskrivna den mänskliga faktorn. Flera olika faktorer bidrar till slutsatsen att det nordiska kraftsystemet förmodligen kommer att utsättas för fler och större prövningar i framtiden samtidigt som marginalerna i systemet minskar.

Ett antal historiska storstörningar beskrivs och analyseras med fokus på utlösande faktorer och grundorsaker som troligtvis kommer att bli vanligare i det framtida nordiska kraftsystemet. Andra storstörningar bidrar med insikter om sannolika händelseförlopp i Norden och en tredje kategori är relevanta med avseende på hur kärnkraftverk påverkats av och kunnat påverka storstörningen.

I Norden har kärnkraftverken potential att ytterligare stötta kraftsystemet under störningar och i instabila lägen. Utifrån det perspektivet är de främsta fördelarna med kärnkraftsenheter, jämfört med andra produktionsenheter, deras storlek, att de är synkrona, att deras primära energikälla är lagringsbar och att de är belägna nära höglastområden. Specifika exempel på potentiellt stöd skulle kunna vara reaktiv störningsreserv, bidrag till FCR-N i båda riktningar vid normal drift, få ersättning för den inertia som kärnkraftsenheterna bidrar med, bidrag till FCR-D i båda riktigninar och att fortsätta vara anslutna till nätet så länge som möjligt vid en störning, diversifierade frånkopplingsnivåer för olika kärnkraftsenheter för att undvika simultan frånkoppling av flera stora enheter, installation av rätt dimensionerade och styrbara bromsmotstånd för att effektivt dämpa stora och relativt långsamma pendlingar, implementera smarta ställverkslösningar, avancerade skydds- och kontrollösningar och införa effektiva nätvärn på selektiva och probabilistiska grunder.

List of Abbreviations

GINO	Grid Interference on Nuclear power plant Operations
NPP	Nuclear Power Plant
HVDC	High-Voltage Direct Current
FCR-N	Frequency Containment Reserve - Normal
FCR-D	Frequency Containment Reserve - Disturbed
PMU	Phasor Measurement Unit
EDT	Eastern Daylight Time
TSO	Transmission System Operator
NASPI	North American SynchroPhasor Initiative
HVAC	High-Voltage Alternating Current
STATCOM	STATic Synchronous COMpensator
ENTSO-E	European Network of Transmission System Operators for Electricity
RfG	Requirements for Generators
UCTE	Union for the Co-ordination of Transmission of Electricity, now part of ENTSO-E
IAEA	International Atomic Energy Agency
RTP	Rated Thermal Power
VPN	Virtual Private Network
SCADA	Supervisory Control And Data Acquisition
EPC	Emergency Power Control
FFR	Fast Frequency Reserve
PSS	Power System Stabilizer

List of content

1 Introduction

The aim of the Energiforsk program called Grid Interference on Nuclear power plant Operations, GINO, is to gain a better understanding of how the operation of nuclear power plants are affected by factors related to the external grid, and to minimize these interferences. The outcomes of this program benefit the Nuclear Power Plants, NPPs, in terms of avoidance of outages and maintenance periods, fewer unplanned shutdowns and lower cost of component replacement. In addition, the outcomes benefit the stability and resilience of the grid, as the ability of the NPPs to stay in operation can be improved, especially during straining events. Energiforsk has within this program ordered a report from DNV where historical big events, such as trip of big power producing units or HVDC links, are investigated.

The project has been performed with the support of a reference group and we would like to thank them for their expertise and feedback that has greatly contributed to the making of this report. We would also like to thank Imtiaz Hoque, DNV, for review of the document and Ambra Sannino, DNV, for sponsoring the project.

1.1 PROJECT OBJECTIVE

Poor profitability has led to the decommissioning of four nuclear power units in recent years in Sweden resulting in only three remaining nuclear power units in Southern Sweden. This reduction in large synchronous power generation together with an increasing amount of converter connected renewable energy, significantly changes the properties of the power system in terms of reduced inertia and reduced short circuit power.

The aim of this project is to investigate the importance of the remaining nuclear power units from a grid perspective, based on historical events put into a Nordic context of today. The focus of this project has been on how the nuclear power units can support the system during big events, as well as how they may support the grid in a post-event scenario.

1.2 PAST PRESENT AND FUTURE NORDIC POWER SYSTEM

Like all global power systems, the Nordics is experiencing a change in generation mix, from large synchronous generators, connected at higher voltage levels, to converter connected generation, connected to all voltage levels throughout the system. This leads to less inertia and less short-circuit power in the system. The primary energy source of renewables is not plannable which results in less predictable power production. A more decentralized power production is less controllable and the distribution grid including embedded generation needs new types of protection systems, taking into account the multiple fault current in-feeds.

More and more large HVDC connections are emerging in the Nordic transmission grid; links to other systems, internal links, and connection links to offshore generation. These links and connections appear more vulnerable and prone to trip for grid disturbances, than traditional synchronous generators.

Also, the load side, including export, is expected to become less predictable in the future although the potential to control the demand seems to be increasing.

The energy transition leads to increased electrification and consequently a higher utilization of the power system.

From a regulatory perspective, grid code requirements are expected to expand and there will be market-based solutions implemented for ancillary services in the Nordics.

Climate change will lead to more frequent extreme weather conditions that can trigger multiple faults that traditional power systems are not designed to withstand.

The Nordic power system is becoming more and more digitized. The benefits of this development include the potential to collect and access large volumes of data, to automate data analysis and to facilitate all types of communication. There are also associated risks, such as introducing a vulnerability to cyber-attacks, new types of human errors, and possibly new types of control interaction issues.

In summary, several different factors seem to contribute to the conclusion that the Nordic system will probably be exposed to more stress in the future while the margins in the system are decreasing, e. g. more and more frequent and long duration operation at transfer limit between the price areas in Sweden.

1.2.1 NPPs in the Nordic Power System

The Nordic NPPs are large units connected at high voltage level at geographical locations near high load centers. Thanks to their primary energy source being storable, the power output of NPPs is plannable. Moreover, NPPs greatly contribute to the inertia since they are connected to the grid via a highspeed synchronous generator with a heavy turbine, and automatically react to active power imbalances without any control systems. Furthermore, the largest unit in the Nordic system, Olkiluoto 3, has recently been commissioned, which means a welcome contribution to the system inertia and local voltage control.

Up until today, the Nordic NPP settings have been set to comply with formal requirements and the Nordic NPPs have not further contributed to market-based ancillary services or emergency support. There might be an untapped potential to do more in the borderland between formal requirements and security limits.

The NPPs rely on strong power system connections and have the potential to mitigate large system events and help prevent near-misses from turning into real misses. In fact, it may be that studying historic real misses does not reflect the greatest contributions of the NPPs to grid resilience.

1.3 BIG EVENTS

The Nordic power system is designed according to the N-1 principle: the system should withstand the loss of any component while keeping synchronism intact, all production and load connected and all system parameters within allowed margins. Parts of the system are designed to handle the simultaneous loss of two components (N-2). /1/

1.3.1 Triggering Event

Triggering event is what sets off the disturbance and can be for example:

- a weather-related event, like a lightning strike
- a component failure
- an operational error
- an accident or a sabotage

Regardless of the triggering event, a power system should be designed to lose one system component and still supply power to all load objects connected, without any violation of operational conditions, such as voltage, thermal, or frequency.

1.3.2 Root Cause

The root cause of a disturbance is the reason why a power system did not withstand the triggering event that set it off. It would typically be a breach of the N-1 condition, either more than one simultaneous fault or lack of resilience to withstand one fault.

Examples of more than one simultaneous fault:

- Weather conditions affect geographically close components simultaneously
- Sabotage - attacking more than one component simultaneously
- Uncorrelated faults

Examples of lack of resilience to withstand one fault:

- Faulty protection components or settings and inappropriate control settings
- Insufficient margins in operation

1.3.3 System State Variable Consequences

Different triggering events and root causes can lead to a variety of consequences for the system state variables:

- Frequency
- Voltage
- Angular stability

Loss of production or load leads to frequency deviations while loss of transmission capacity leads to voltage deviations and/or oscillations at an initial stage. The development of the situation may then lead to any combination of consequences for the system parameters.

1.3.4 End states

Triggering events that for different root causes lead to deviations in the system parameters may lead to the following end states, listed from best to worst case:

- Deviations of system parameters within margins, no production or load damaged or disconnected
- Deviations of system parameters outside margins, production or load exposed to risk of damage but not disconnected
- Deviations of system parameters outside margins, production or load exposed to risk of damage and partly disconnected
- Blackout of parts of or of whole power system

Loss of synchronism between parts of the power system is difficult to place on the list in terms of severity, since it may not cause any trouble for production or load customers if adequately solved, or it may be a step on the way to the more severe end states listed above.

2 Methodology

In this chapter the methodology for the analysis is explained.

DNV has performed a literature search to identify relevant big events that together form a set that:

- are relevant to the Nordic grid
- represent a variety of root causes
- represent a variety of disturbance types
- are relevant from an NPP perspective
- represent both national and international experiences

For each entry on the list, the triggering event, the root cause, the system consequences and the end state will be identified.

Some events represent triggering events and root causes that are likely to become more significant in the future. Other events provide insights into likely courses of events for the Nordic power system. A third category is relevant for the effect on and potential of NPPs during big events.

In Chapter 3, each event is described according to the following four steps with emphasis on the main learnings from each event respectively:

1. Describe the actual system, where the disturbance occurred, e.g. Nordic, European, or Northwest US/CA synchronous system.
2. Describe the operational conditions, reserves, etc., immediately before the disturbance.
3. Describe the sequence of events, during the disturbance: Identify the root cause of the disturbance. Root cause in this context is the unexpected condition or event, that caused the disturbance or blackout, which is not always the same as the triggering event. Describe the likelihood of such a cause of a disturbance happening in the present and future Nordic grid.
4. Describe the critical quantities (voltage, frequency, oscillations, impedances, etc.), before during and after the disturbance. This will be done both for the actual event and when applying the disturbance profile from the historical event in a point of possible connection of a Nordic NPP.
   a. Describe how these quantities affected / could have affected the NPP unit and its auxiliaries. Note if the NPP reacted correctly or not.
   b. Describe effects of impact on the external grid if faults occur inside the plant, as a consequence of the disturbance.
   c. Momentary as well as long term effects will be considered.

In Chapter 4, the potential of NPPs with regard to big events in the future Nordic power grid is addressed per disturbance type in the following steps:

1. Identify actual and potential support from the NPP to the grid, to mitigate the consequences of the disturbance.
   a. Actual support refers to the present design and operation of the Nordic NPPs.

   b. Potential support refers to – what can be added, e.g. in terms of fast valving, breaking resistors, etc.
2. Compare the support identified in 1), with the support from a converter connected generating unit, with minimum performance capability, of the same size as a Nordic NPP.

Triggering events and root causes that are new or likely to become more frequent in the future Nordic power grid are discussed in Chapter 5.

In Chapter 6, the conclusions on how nuclear power plants may mitigate big events that could arise in the future Nordic power grid are summarized.

3 Events

The following table lists the identified events from the literature search that are considered most relevant and that together form a set of big events that:

- are relevant to the Nordic grid
- represent a variety of root causes
- represent a variety of disturbance types
- are relevant from a NPP perspective
- represent both national and international experiences

Table 1 List of big events that will be discussed in Chapter 3.

Event	Triggering event	Root cause	System State Variable Consequences	End state
Hamra (1983)	Component failure: overheated disconnector	N-1 not fulfilled: system could not withstand the disconnection of two major transmission circuits, resulting from expected protection setup of the ABC type substation	Voltage deviation and frequency deviation	Blackout of parts of or of whole power system: 7000 MW disconnected for several hours in Southern Sweden
North West coast substation (1997)	Weather: ice in a shaft led to a one phase earth fault in the transformer station	N-1 not fulfilled: insufficient margin in the system operation	Oscillations	Deviations of system parameters outside margins, production or load exposed to risk of damage and partly disconnected: Oscillation and final disconnection of two Ringhals units and disconnection of small amount of load in Southern Sweden

Event	Triggering event	Root cause	System State Variable Consequences	End state
Salt storm in Southern Sweden (1999)	Weather: strong wind resulted in dry salt on transmission line insulator chains	More than one fault: more than one transmission line tripped due to the same triggering event	Not applicable	Deviations of system parameters within margins, no production or load damaged or disconnected: No load was shed, and no generation was affected, but the transmission system capacity was severely reduced.
Zeeland and Southern Sweden (2003)	Component failure: valve fault in Oskarshamn 3 and overheated disconnector in a west coast substation	More than one fault: uncorrelated faults	Frequency deviations and voltage depression	Blackout of parts of or of whole power system: Voltage collapse and Southern Sweden without power for up to 7 hours
South Florida (1985)	Weather: brush fire destroying three parallel 500kV lines	More than one fault: more than one transmission line tripped due to same triggering event	Voltage deviations	Blackout of parts of or of whole power system: Voltage collapse and blackout within seconds

Event	Triggering event	Root cause	System State Variable Consequences	End state
North America Blackout (2003)	Operational error: too low margins lead to the disconnection of generation units	N-1 not fulfilled: insufficient tree trimming, IT issues, and low margin in system operation	Voltage deviations	Blackout of parts of or of whole power system: Blackout affecting 45 million people, power not fully restored until two days later
Underfrequency event London (2019)	Weather: lightning strike led to trip of transmission line	N-1 not fulfilled: faulty protection settings (control settings of offshore wind plant) and breach of grid code regulations by production owner	Frequency deviations	Blackout of parts of or of whole power system: Blackout affecting 1,1 million people, lasting 15-45 minutes
Separation of continental Europe (2006)	Line disconnection to allow for a ferry boat to pass	N-1 not fulfilled: Underestimation of the margins	Frequency deviations	Loss of synchronism: System split into two synchronous areas with opposite deviations in frequency for the two parts

Event	Triggering event	Root cause	System State Variable Consequences	End state
Ukraine Cyber Attack (2015)	Sabotage: Cyber attack	More than one fault: more than one breaker opened simultaneously	Not applicable	Blackout of parts of the power system.
Loss of NordLink HVDC (2022)	Trip of the link. The exact triggering is unknown. Often internal issues in the control system of the link	N-1 fulfilled: Probably internal HVDC link issues.	Frequency deviation	Deviations of system parameters within margins, no generation or load damaged or disconnected
Loss of several units in Lule river (2005)	Breaker failure protection activated, and delayed earth-fault protection	More than one line tripped: Stuck circuit-breaker in one pole, causing dissymmetry	Frequency deviation and system islanding	System separation
Loss of Oskarshamn 3 (2011)	Planned trip, due to tests	N-1 condition fulfilled: Planned trip, due to tests	Frequency deviation	Deviations of system parameters within margins, thus a low frequency minimum of 49.36 Hz

3.1 HAMRA (1983)

On the 27th of December 1983, a disconnector overheated and fell to the ground in the substation Hamra and caused a busbar fault. The substation was equipped with a common section and replacement breaker and when this breaker was used to disconnect the fault, the busbars were split, and two busbars were disconnected instead of only one. This disconnection led to a cascade of other disconnections of high voltage links, and the south of Sweden lost connection to the north, to Norway and to Denmark, and some parts were without power for up to 6 hours.

Svenska kraftnät has taken actions to reduce the number of these types of ABC-switchgears by designing new or refurbished substations differently, and the likelihood of this type of event happening again is deemed small. /1/

The south part and the initial disturbance are not regarded for further investigation, since they are well known and represent a typical voltage collapse initiated by loss of transmission capacity. The north part however, after the system split, is chosen for deeper investigation, especially concerning the response from the Finnish NPPs.

3.1.1 Deeper Investigation of the Northern part of the System

This deeper investigation is based on a number of different reports. /2//3//4//5/

The north part of Sweden and Finland survived the disturbance with a significant frequency overshoot. The generation surplus in this part of the system was about 6000 MW, which accelerated the system to a temporary overfrequency of 54.0 Hz after 5 seconds. A number of hydro units were disconnected due to the high frequency. Together with the turbine control of the remaining hydro units, this brought the frequency down to 50.05 Hz within 12 seconds after the system separation.

The power export to Finland from the northern network increased after the system separation. The Finnish system was accelerated to the same frequency as that in Northern Sweden. However, in Finland only one north-south 400 kV line was in operation because of work on the other one. This line then tripped on overload.

Before the disturbance the load in Finland was about 6000 MW, supplied as

- Nuclear power 2250 MW
- Hydro power 1500 MW
- Other thermal power 1500 MW
- Import from Soviet Union 630 MW
- Import from Sweden 115 MW

The nuclear units TVO I and TVO II were both online at 103 % and about 90% power respectively. The south going power across the Ule river in Finland was about 340 MW. The voltages were normal, with a quite light transmission situation. Except for the disconnected 400 kV line to Sweden, the Finnish system was in normal switching stage. The net import from Sweden was such that 200 MW was imported on the only 400 kV line and 85 MW was exported back to Sweden on the 220 kV connection to Sweden, which was a normal situation.

The export from Sweden to Finland was only 115 MW before the disturbance. At the system separation, a large portion of the Swedish generation surplus was used to accelerate the Finnish system. The frequency increase in Finland was therefore initially the same as in Sweden. Since only one 400 kV connection between Sweden and Finland was in operation at the moment, the power increase on this line was so large that it tripped for overload. The 220 kV connection to Sweden, however, remained in operation, but the surrounding Swedish area was separated from the rest of the Northern Swedish grid, due to overload on the 130 kV level. Thus, the surrounding swedish area was supplied from the Finnish 220 kV system. The connection between Sweden and Northern Norway was also interrupted, leaving the north of Sweden as an isolated system.

From the Loviisa NPP in Southern Finland it is reported that after the disconnection of Southern Sweden, the export to Finland increased and was roughly 900 MW and the frequency increased to around 50,6 Hz. Then the only remaining 400 kV line between Finland and Sweden tripped. After the disconnection from Northern Sweden, the frequency dropped and was about 49,8 Hz. After that the frequency dropped further and the lowest value was 49,4 Hz. The frequency recordings from Loviisa are presented in **Fel! Hittar inte referenskälla.**. The frequency control in both the Loviisa units increased their power outputs to their maximum values. After another 20 minutes the power was returned to normal, due to a stabilization of the frequency. Both the Loviisa units stayed grid connected and contributed to the stabilization of the grid, by frequency control.

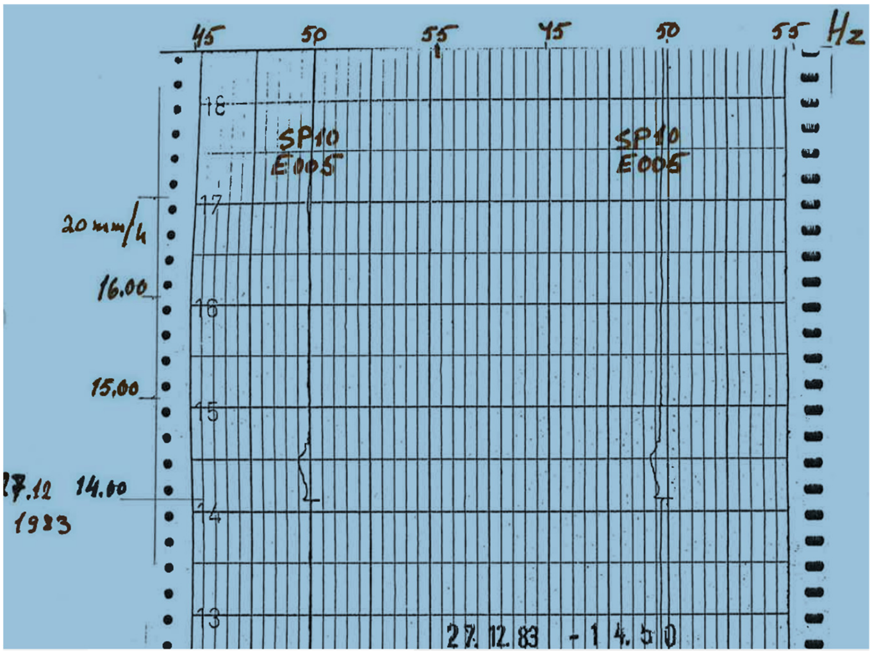
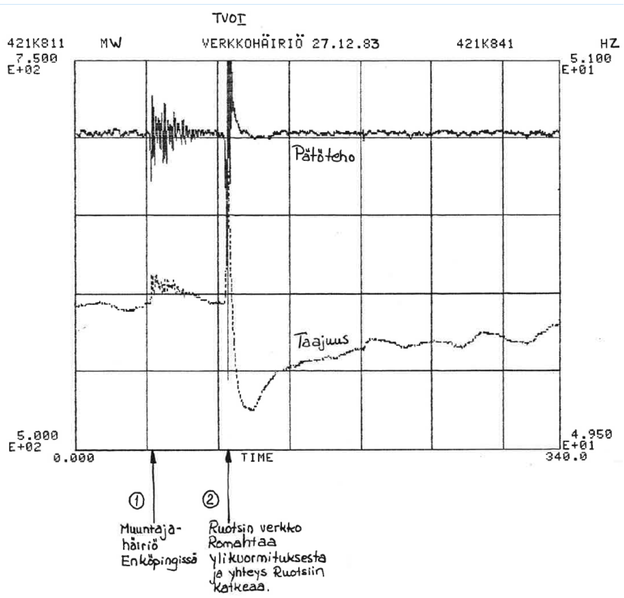


Figure 1 Frequency recording from the Loviisa NPP in Southern Finland. /3/

When the 400 kV line between Finland and Sweden tripped, it caused major power swings in Olkiluoto, the largest peak-to-peak value was about 275 MW. At the time of the disturbance, the frequency rose to approximately 50.7 Hz, which then rapidly decreased and was the lowest at 49.65 Hz. The frequency rose slowly again to almost 50 Hz and started decreasing about 5 minutes after the disturbance. Only after about 30 minutes the frequency was normal again. The 400 kV voltage faced oscillations, which was 413 kV at the highest and 383 kV at the lowest. After the fault, the 400 kV voltage continued to fluctuate. This caused voltage oscillations to the 6.6 kV voltage, which was about 6.9 kV at the highest point and about 6.1 kV at the lowest point. The voltage oscillations were highly damped. Voltage and frequency oscillations in the power plant internal grids caused disturbances for the AC motors. The rotational speeds of reactor main circulation pumps and water infeed pumps had very small changes. The change in the feed water pumps rotational speed was about 90 rpm. Because the water supply pumps have their own speed control, permanent frequency deviation does not affect their rotational speed. Changes in the speed of the pumps did not cause disturbances for the process operations, although there was a small change in the infeed water flow. There were no changes in the reactor surface, pressure or neutron effect.

Gas turbines started and hydro power in Northern Finland increased its power. One of TVO's shareholder Rauma-Repola at the Rauma mills, experienced load shedding. The frequency relays had a setting of 49.5 Hz and they dropped approximately 7 MW of the mill's load. According to the joint operation agreement, all spinning reserves must be activated at a frequency of 49.5 Hz. Activation means either an increase in (generated) power or a decrease in loads. There were no other disconnections among TVO's shareholders. Figure 2 shows some TVO measurements.

After the separation from the Swedish system, the operational conditions in the Finnish system were normalized. Any additional trips or disturbances have not been reported.



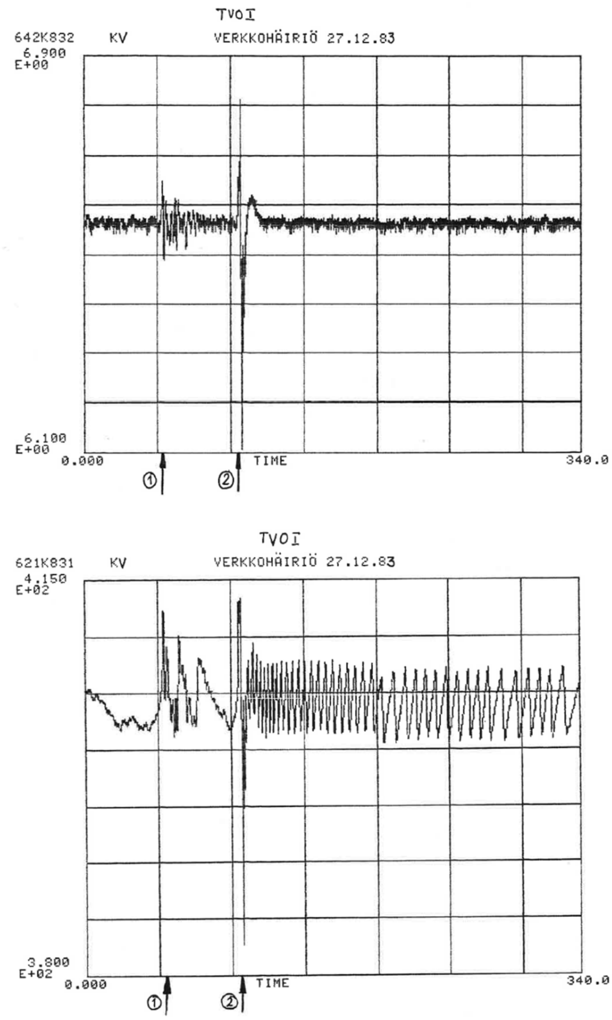


Figure 2 TVO Measurements /4/

3.1.2 Conclusions and lessons learned from the deeper investigation

System separations may cause significant frequency excursions, where the underfrequency conditions are quite well studied and remedial actions prepared to counteract the frequency drop. However, not much attention is paid to the overfrequency part of the system, since the system most often survives. The following lessons can be learned from the overfrequency part of the system.

1. The overfrequency trip of the generation units should not be set at the same level and the same time delay. Diversify the settings with respect to frequency level and/or time delay to achieve a “smooth” disconnection of generation to safely bring the frequency back to 50 Hz. Such a coordination is the responsibility of the TSO.

3.2 NORTH WEST COAST SUBSTATION (1997)

On the 1st of January 1997, a single phase-earth fault in a north west coast substation (NWCS) occurred due to ice in a bay. The busbar protection detected the fault and correctly tripped the associated breakers in the substation, which meant a disconnection of the 400 kV line between NWCS and a west coast substation (WCS) which carried a heavy load from the south of Sweden to the north. When the line was disconnected, the generation from the nuclear power plants Ringhals 1 and 2 had to take the route down by south west coast substation (SWCS) instead, which resulted in growing power oscillations on the transmission grid.

The oscillations caused the under impedance protection to disconnect Ringhals 1, and the distance protection disconnected the line between Ringhals 2 and WCS, which meant that both Ringhals 1 and 2 were disconnected from the grid. The following voltage oscillations resulted in a disconnection of a small amount of load in the southwest of Sweden.

After this incident, a lower load limit on the 400 kV line between WCS and another west coast substation has been implemented in order to be able to suppress oscillations in case a similar event should occur. With the growing amount of renewable energy sources installed in the system there is a risk that unforeseen oscillations could occur in the future. Svenska kraftnät confirms that unforeseen oscillations have also occurred, e. g. during planned outages. /1/

This disturbance is chosen for deeper investigation, since it is not so well known, and it is one of very few that involves undamped oscillations. The situation development after the fault clearance will be emphasized.

3.2.1 Deeper Investigation

The main part of this deeper investigation is based on one report from Svenska kraftnät /6/ and one from Sydkraft /7/.

Immediately before the incident the load in Sweden was around 20 000 MW. Except for Oskarshamn 1, all the Swedish nuclear units were in operation. The grid was in normal switching state. Import from Zealand, Jutland and Germany, and export to Norway caused a power flow towards the north on the west coast of Sweden. When the bus bar protection trips, WCS-NWCS and NWCS-inland substation (IS), will be disconnected.

The primary fault, ice in the transformer bay causing an earth-fault in R-phase on the connection between T2 and bus bar A in NWCS, was properly cleared by the bus bar protection. Since the current transformer for the bus bar protection was located in the transformer bushing, the bus bar protection was used to protect the connection between the transformer and the bus bar. After the bus bar protection had tripped all the breakers connected to bus A, the fault current infeed continued from the 130 kV side of the transformer. This fault current contribution was interrupted after 240 ms, most likely by the bus bar backup protection. The switchyard in NWCS, with the fault location, circuit-breakers and current transformers, is shown in Figure 3.

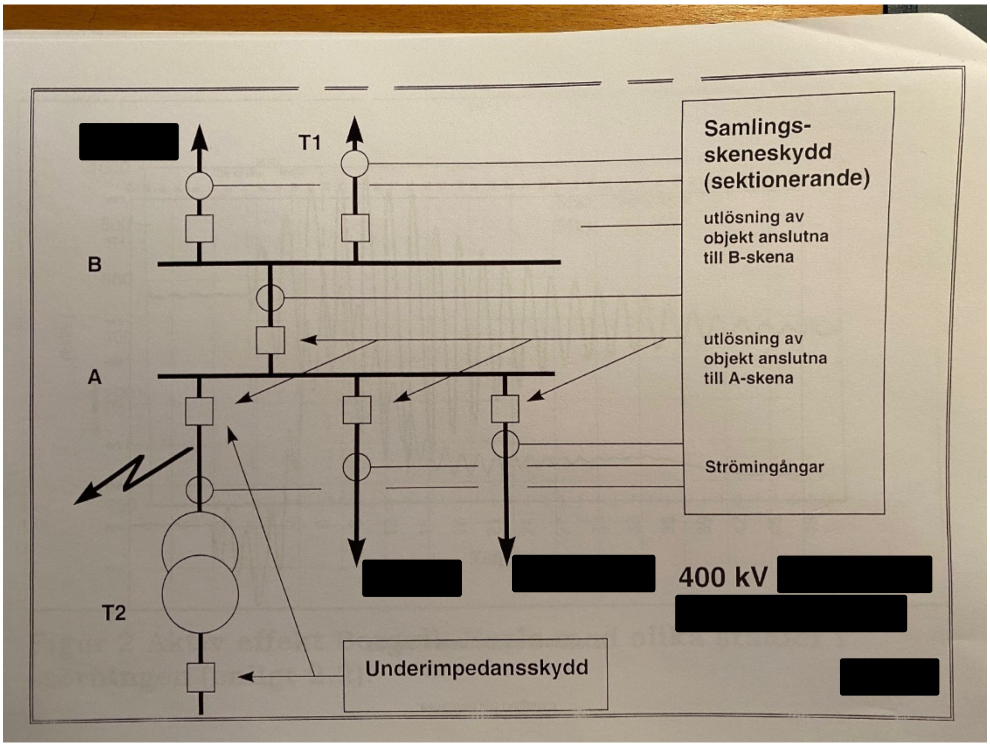


Figure 3 400 kV switchyard in NWCS/7/

Looking back to Figure 3, we see that after the trip of the WCS-NWCS line, all the power from Ringhals 1 and Ringhals 2 has to go all the way down to SWCS, and then back north, before getting a firm connection to the rest of the meshed grid. Moreover, imported power from Zealand is injected in SWCS. In one shot, the impedance between the two Ringhals units and the rest of the grid is considerably increased. Therefore, the power output from the Ringhals units started to oscillate, with growing magnitude. Unfortunately, no recording from Ringhals has been available.

The frequency in the system during the disturbance is shown in Figure 4. Discontinuities are observed in the figure for the fault occasion, the trip of an underlying 130 kV connection, and for the trip of Ringhals 1 and Ringhals 2. The frequency dip down to 49.4 Hz is considerable. However, with respect to the total loss of 1700 MW, the frequency dip is not alarming.

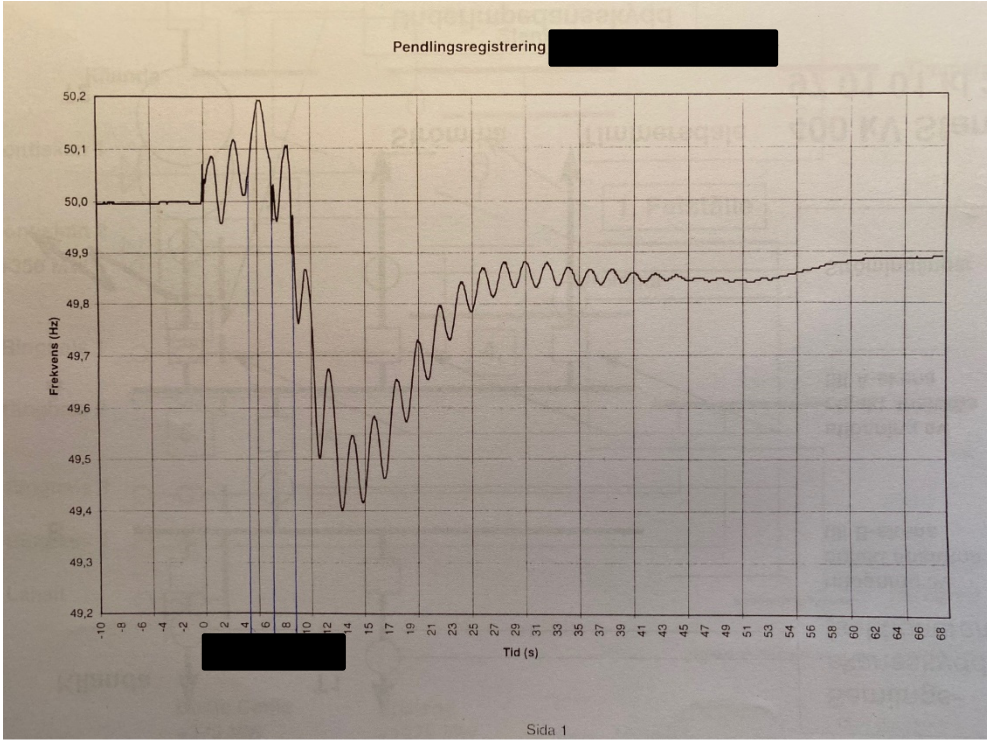


Figure 4 System frequency recorded in SWCS /7/

The severe active power oscillations between Norway and Sweden are illustrated in Figure 5, with peak-to-peak values exceeding 1000 MW.

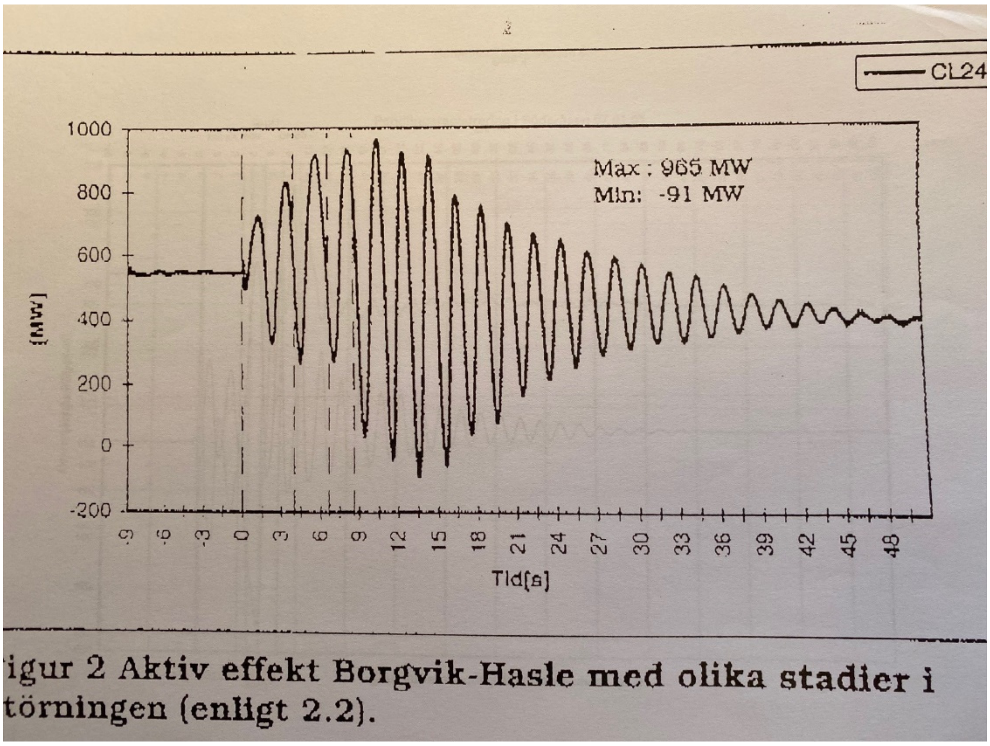


Figure 5 Active power from connection to Norway, recorded on Swedish side /7/

The active power from Barsebäck to SWCS is shown in Figure 6, when the fault occurs and the power from the Ringhals units is forced towards SWCS and the active power from Barsebäck to SWCS is reduced. The power from Barsebäck has to find other paths towards the grid. When the Ringhals units trip, the Barsebäck power is redirected towards SWCS.

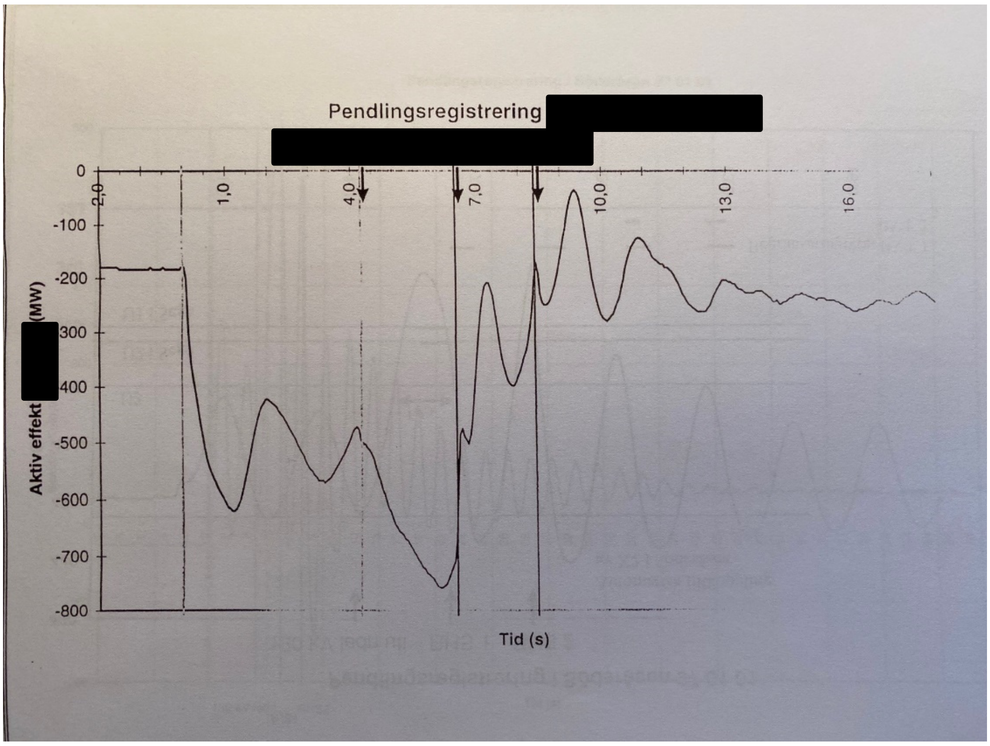


Figure 6 Active power from Barsebäck to SWCS, recorded in SWCS /7/

The reactive power oscillations from Barsebäck to SWCS are growing in magnitude until both the Ringhals units are tripped, see Figure 7.

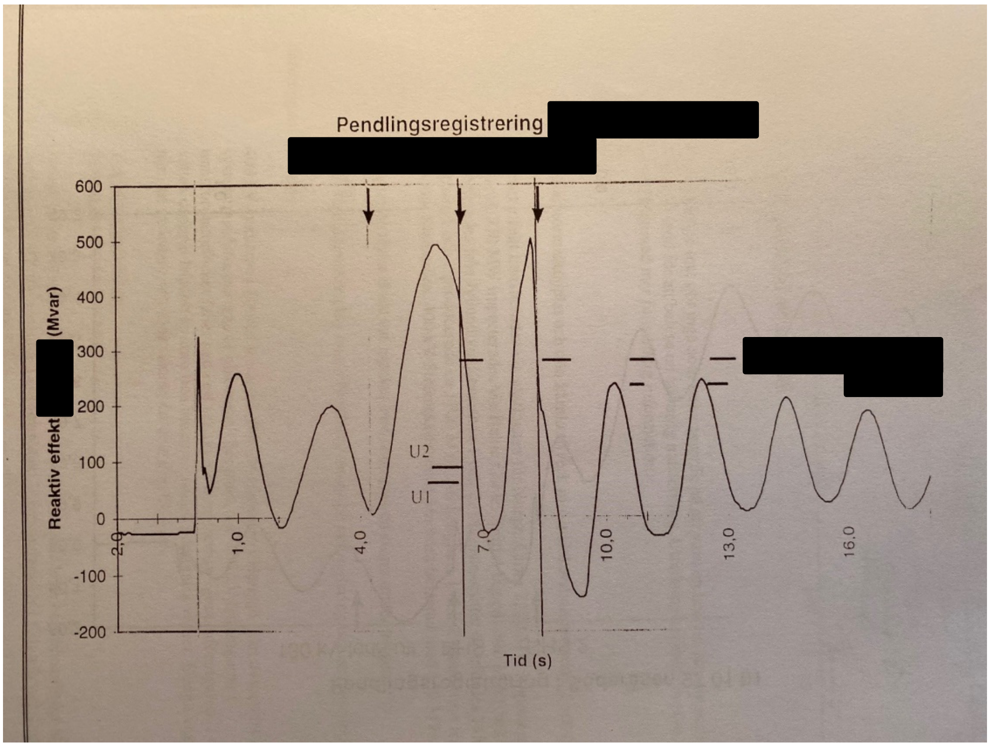


Figure 7 Reactive power from Barsebäck to SWCS, recorded in SWCS /7/

3.2.2 Conclusions and lessons learned

It is clear from the analysis that the system was not N-1 dynamically stable for a fault on and permanent trip of the WCS-NWCS line, given the operational conditions. The following can be learned from the disturbance.

1. Line trips will change the impedance conditions in the network. Certain line trips might increase the impedance between generation and the rest of the grid so much that a) undamped oscillations occur, or b) there is no stable operation point, given the impedance and the active power output.
2. Power oscillation triggered fast *generation curtailment* might be an attractive solution to damp the oscillations, without tripping the production unit(s).
3. Fast oscillation damping, e. g. with properly controlled braking resistors, might be an attractive solution to damp large oscillations, without tripping the production units(s).

3.3 SALT STORM IN SOUTHERN SWEDEN (1999)

In February 1999, salt had built up on insulators on transmission lines in the south of Sweden, and due to prolonged cold weather, the consumption was unusually high. On the 11th of February at 11.02, the 400 kV line SWCS – Barsebäck tripped due to the salt coating, and at 11.15 the 400 kV line Barsebäck – to south located substation also tripped for the same reason. The 130 kV grid became overloaded as a result, and the export on the DC link to Germany (Baltic Cable) was reversed to import. Gas turbines were started in the affected region.

The 400 kV line between another west coast substation and SWCS tripped at 11.40 and the 400 kV line between a substation on the west coast and SWCS tripped at 11.52, due to the salt coating, and the whole of south of Sweden was dependent on the remaining 400 kV line. The nuclear power plant Barsebäck was in operation and connected only via single circuit to the 400 kV system. Barsebäck was instructed to decrease it's power to 60% to alleviate a potential transition into house operation. No loads were disconnected. /8//1/

This disturbance is not regarded for further investigation since the NPPs were not affected.

3.4 ZEELAND AND SOUTHERN SWEDEN (2003)

On the 23rd of September 2003 two non-related events led to an extensive power outage in Southern Sweden and Eastern Denmark. At 12:30, the nuclear power plant Oskarshamn 3 was manually shut down due to a valve fault, first from about 1200 MW to around 800 MW, and then down to zero, all within 20 seconds. Five minutes later, what seems to be completely independent, a two-phase short circuit occurred in the substation on the west coast.

A disconnector overheated, which could not have been caused by the increased load current due to the disconnection of Oskarshamn 3, unless it was faulty. The disconnector had been maintained according to current instructions. The damaged disconnector fell to the ground in such a way that it caused a fault on the other fully functioning busbar. The busbar protection detected the fault and sent correct trip signals to the associated breakers.

Breakers for all objects connected to both the busbars were tripped, and among them were the radial lines to the nuclear power plants Ringhals 3 and Ringhals 4. This meant that the south of Sweden was now completely powered via the 400 kV lines in the eastern part of Sweden. After 90 second, a voltage collapse occurred, and 1.5 million people in Sweden were without electricity for up to 5 hours, and 2.5 million people in Denmark were without electricity for up to 7 hours. Svenska kraftnät had already before the event noticed negative features with the type of switchgear present in the substation on the west coast, and has since then undertaken actions to rebuild similar switchgears so that the fault that happened in 2003 would not happen again. /1/

This disturbance is unique, since it comprises a combination of non-dimensional loss of generation and non-dimensional loss of network in the Nordic system; loss of approximately 3000 MW and a 400 kV bus-to-bus fault in the substation at the west coast, within 5 minutes. The system survived with respect to frequency, without triggering the automatic underfrequency controlled load shedding system (starting at 48.8 Hz). This will most probably not be the case today, due to less FCR-D. Due to the loss of generation in the south, a number of tripped transmission lines, transmission lines out of operation due to maintenance, and all HVDC links southwards out of operation, the power transmission from the north increased on remaining lines. Due to load recovery (transformer tap-changer operations, etc.) and correlated decreasing voltage, the first distance protection tripped a major transmission line after about 1 minute, and the voltage collapse in the south of Sweden was a fact.

This disturbance is chosen for deeper investigation, since it comprises one of the largest trip of generation ever in the Nordics (1200+900+900 MW) and after about another minute a voltage collapse in the south part of the system. The NPPs in the south part were exposed to a significant drop in frequency, followed by a subsequent drop in voltage. The northern (surviving) part was exposed to an overfrequency at the system separation.

3.4.1 Deeper Investigation

The main part of this deeper investigation is based on a report from Svenska kraftnät /9/.

The affected area for this disturbance is where also the two nuclear sites Ringhals and Oskarshamn are; the distance between Ringhals and Oskarshamn is about 300 km. The phase-to-phase fault at the substation in the west coast tripped all the lines connected to this important substation, leaving all the power to the very South of Sweden and to Denmark on two rather weak transmission lines on the east side. At the time for the disturbance, all three HVDC connections from Southern Sweden/Denmark to continental Europe were out of service (this will not be the situation today due to better planning). A simple form of system protection scheme, measuring the voltage in a few selected points in Southern Sweden and action on the HVDC links was installed at the time for the disturbance, but did not give any support.

The damaged disconnector of pantograph type is shown in Figure 8. The figure also shows how the strong wind from the west caused the arc to blow all the way to the nearest phase on the next busbar. The switchyard was designed in such a way that this type of phase-to-phase fault should not be possible, due to the distance between phase A and phase C in Figure 8. The busbar fault was properly cleared within 100 ms by the busbar protection.

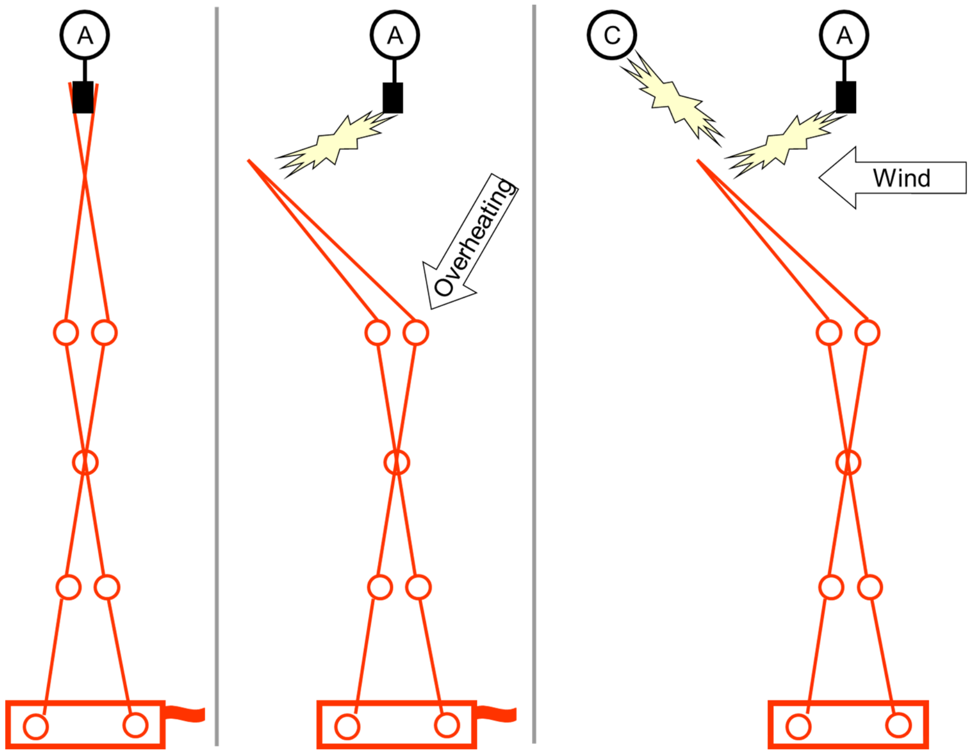


Figure 8 The overheated disconnector, causing a phase-to-phase fault involving two busbars in the substation at the west coast. Modified sketch from /9/

After the trip of Oskarshamn 3, the current through the later on broken disconnector was slightly increased, but not beyond the rated value. The disconnector is shown in Figure 9.

Figure 9 Close up photo of the overheated and broken disconnector in the substation at the west coast.

It is relevant to mention that wind power generation connected at 10 kV level on the island of Öland, about 500 km away from substation on the west coast tripped due to the properly cleared 400 kV fault. This justifies the formal requirements on remaining grid connection for generation due to specific criteria, nowadays specified in grid connection codes for generators.

Figure 10 shows a recording from a 400 kV substation in mid Sweden, with the voltage on bus A and bus B together with the active and reactive power going southwards. The recording shows that the transmission system voltage, quite remote from the affected area is as low as 380-360 kV for about 50 seconds, and in the range of 360-340 kV for about 10 seconds – This is a typical long term voltage collapse scenario, with plenty of time to take prepared automatic remedial actions, such as undervoltage controlled load shedding or blocking of automatic tap-changer regulation. It can also be seen in Figure 10 that the active power decreases and the reactive power increases into the affected area while we are approaching the breakdown and blackout in the southern part.

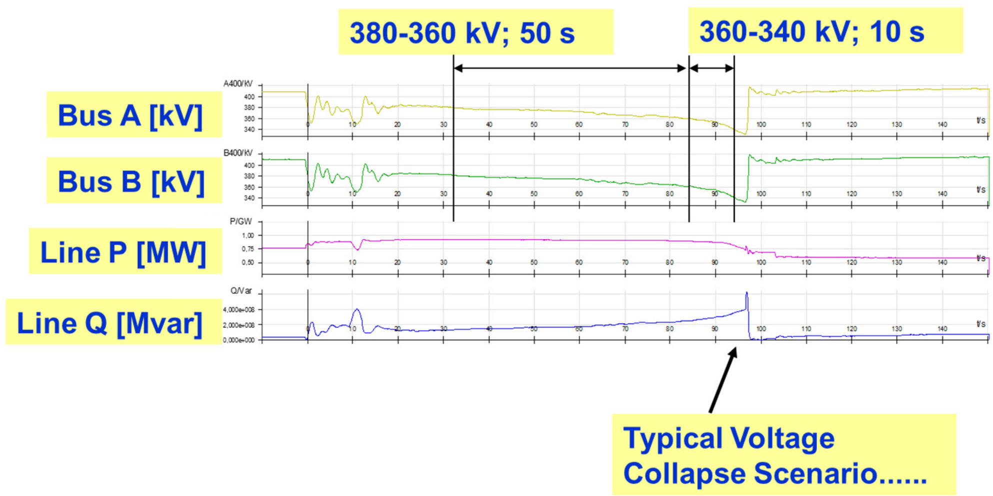


Figure 10 Recording from mid Sweden (slightly north of Stockholm). Modified figure from /10/

The behaviour of a tap-changer on a 400/130 kV transformer close to the Oskarshamn power station is shown in Figure 11. While the voltage was decreasing in the 400 kV transmission system the tap-changer tried to keep up the voltage on the 130 kV system, and thus re-establishing the voltage dependent part of the load – increasing the stress on the 400 kV system even more. It is noted that this tap-changer raised its position 9 steps within 80 seconds. In this stressed situation, there would most probably be a great potential for a more intelligent behaviour of this tap-changer.

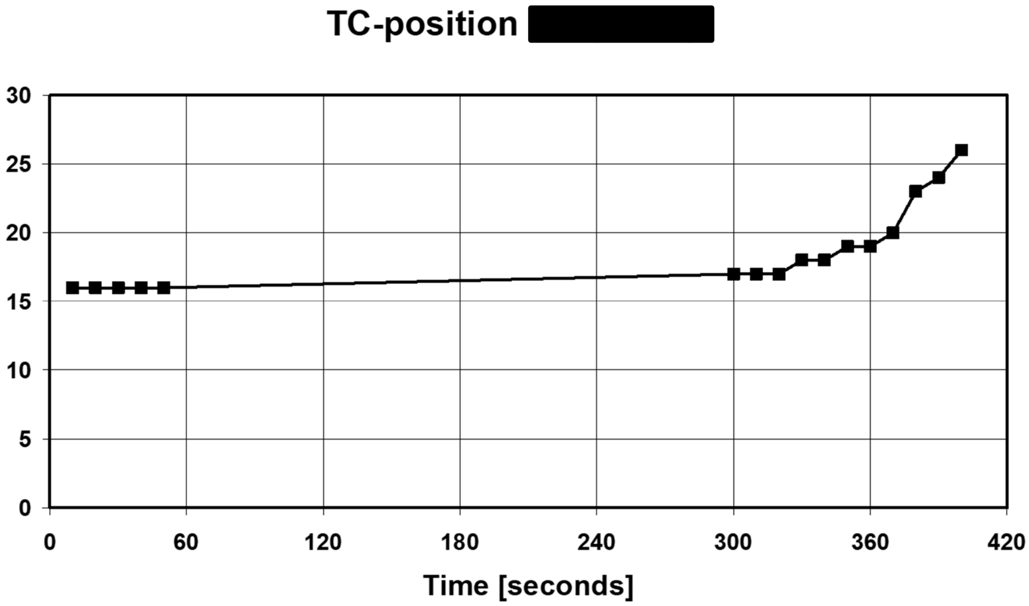


Figure 11 Tap-Changer position at a substation close to Oskarshamn

At the time for the disturbance ABB had Phasor Measurement Unit (PMU) measurements active on the island of Öland. Figure 12 shows the 50 kV voltage on Öland rather close to the Oskarshamn nuclear power station.

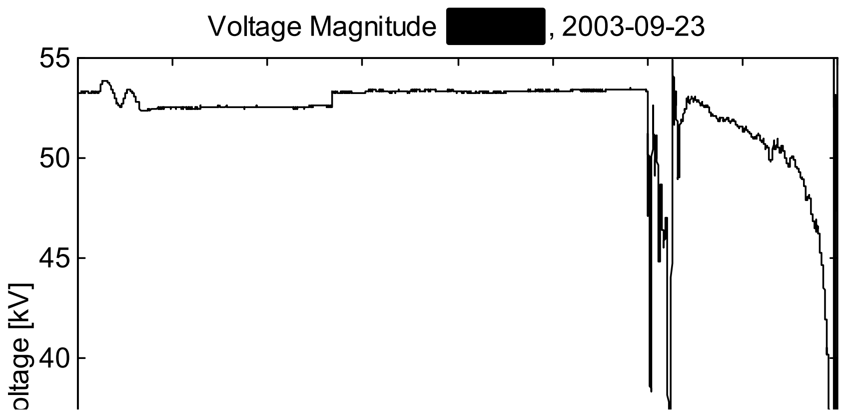


Figure 12 ABB PMU recordings of 50 kV voltage on the island of Öland capturing the blackout

The frequency during this disturbance, as shown in Figure 13, was impressively stable and well above 49.0 Hz for the entire scenario, in spite of the loss of 3000 MW of generation. The frequency recovery immediately before the final breakdown is related to the load relief associated with the reduced voltage.

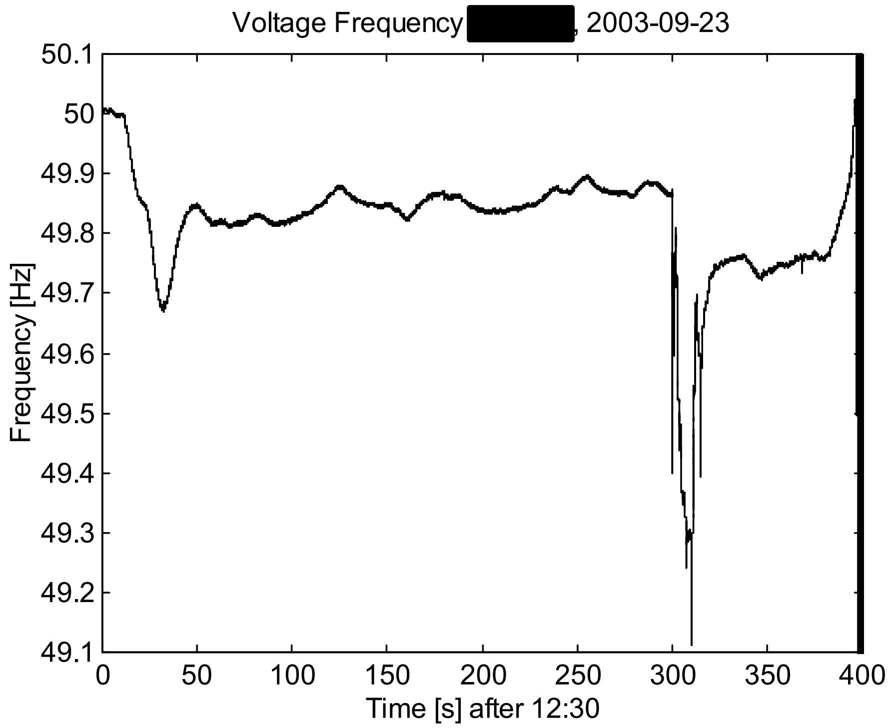


Figure 13 ABB PMU recordings of 50 kV frequency recording at the island of Öland

3.4.2 Conclusions and lessons learned

The Sweden-Denmark disturbance on September 23, 2003, was a typical voltage collapse. The disturbance also included a large loss of generation, but no underfrequency controlled load shedding, since the frequency stayed above 49.0 Hz. The conclusions and lessons learned are summarized below.

1. Disconnectors have been the cause of two severe blackouts in Sweden (1983 and 2003) and should be avoided. Svenska kraftnät nowadays design substations with disconnectors integrated in the circuit breakers.
2. A way to avoid the short circuit in the substation on the west coast is to design the switchyard with the same phase of the two busbars closest to each other, i.e., the two bars involved in the short circuit, should be of the same phase, A<->A or C<->C (refer to the right part of Figure 8). Another way would be to increase the distance.
3. The simple switchyard design in the substation on the west coast at the time for the disturbance is now replaced with a standard 2-bus double breaker design, which would survive the disturbance without any line disconnection.
4. Tap-changer control could be modified (blocked) to avoid worsening the conditions in voltage instability situations. Such blocking functions for abnormal voltages are now available.

5. In the same way as underfrequency controlled load shedding has been applied in most power systems for almost a century, undervoltage controlled load shedding, and other voltage based remedial actions, could most favourably be applied. Synchronized measurements using PMUs could be the basis for such a protection scheme.

3.5 SOUTH FLORIDA (1985)

On 17 May 1985, three lightly loaded 500 kV transmission lines were tripped due to a brush fire. This resulted in a voltage collapse and blackout within a few seconds. Underfrequency relays were prevented from operating due to low voltage, and the load loss was 4 292 MW. /11/

This disturbance is chosen for deeper investigation, since it represents a transient voltage collapse triggered by a sudden loss of significant transmission capacity. The root cause of this disturbance is weather related; in this case brush fire, but the same type of disturbance escalation can result from snow/ice storms, hurricanes, salt storms, etc. The simultaneous loss of transmission capacity is however well covered by the Zeeland and Southern Sweden (2003) event, discussed in Section 3.4.

3.5.1 Deeper Investigation

The main part of this deeper investigation is based on the description found in /11/.

This disturbance is interesting since it is one of very few which resulted in a (fast) transient voltage collapse, and its root cause is related to climate change and conditions applicable to the Nordic system. When the three 500 kV lines tripped within a very short time frame, any remaining connection between the two areas were immediately overloaded and tripped, and thus the breakdown was immediate. Since these kinds of disturbances are rather quick there is not much time for any automatic remedial action. Figure 14 shows system frequency and transmission system voltage for the South Florida blackout on May 17, 1985.

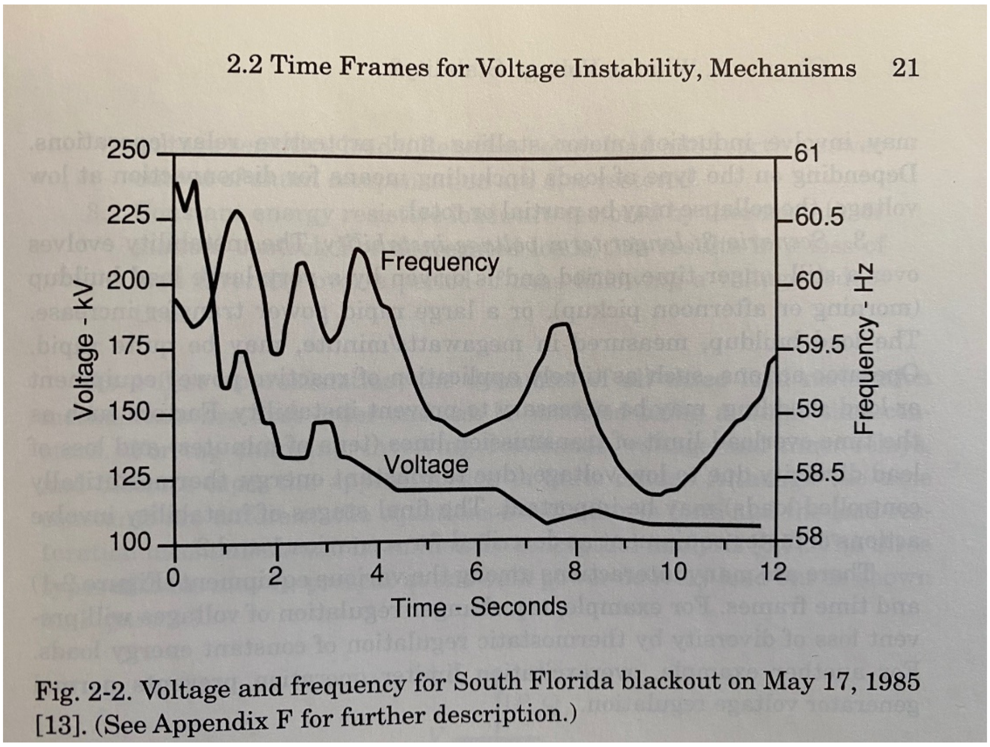


Figure 14 Voltage and frequency excursions immediately after the line trips /11/

The interesting characteristic of this Florida disturbance is the sudden loss of significant transmission capacity, in this case three 500 kV lines, due to a common cause, in this case a brush fire perpendicular to the three lines. Similar disturbances could be caused by ice, snow, salt, flooding, or earthquakes. Falling towers for double circuit arrangements, apparent at several places in the Nordics, would have similar consequences but is not necessarily weather related.

3.5.2 Conclusions and lessons learned

The Florida disturbance represent a transient voltage collapse, with basically no time for remedial actions. The following conclusions can be made.

1. Climate is ever changing, with more frequent extreme weather-related conditions, such as brush fires, that might affect physically nearby parallel lines, causing an N-2 or worse fault, with a common trigger.
2. Parallel lines could for the sake of redundancy and reliability be located some distance apart, to avoid simultaneous failures due to the same triggering event.
3. Double circuit transmission tower design is always an increased risk for common cause failures.
4. Underfrequency relays must be operable also at reduced voltage. /12/

3.6 NORTH AMERICA BLACKOUT (2003)

On the 14th of August 2003, a number of events took place in the northeast of US and Canada that led to one of the biggest outages in history. The load was high, and a number of power plants, lines and shunt capacitors were out of operation. During these conditions, an important generator (Eastlake 5), was disconnected due to too high reactive generation, which lead to a deficit in reactive power, with low voltages as a result. At the same time the grid operator experienced computer issues and lost capability to monitor the grid.

Several lines were heavily loaded and due to sagging, there were flashovers from some of the lines to trees on the ground. During a 35 minutes time frame, five 345 kV lines were disconnected, and as a result even more lines were overloaded, leading eventually to a voltage collapse. If it hadn't been for the software bug, the operator would have been able to see the need for redistribution of load and the cascade could have been avoided. In total, more than 60 GW of load was lost. The power outage affected 45 million people in 8 U.S. states, and full power was not restored until two days later. /1//13/

This disturbance is chosen for deeper investigation, since there are many aspects and NPPs involved. Especially, since some NPPs remained grid connected while others tripped.

3.6.1 Deeper Investigation of the North America Blackout (2003)

This deeper investigation is primarily based on the Final report from the U.S. and Canada Task Force /13/.

Conditions prior to the blackout:

- A warm but not unusually warm day in August
- A number of generation units were on planned outage
- High power transfer to northeast US and to Ontario
  - Not unusually high and not above transfer limits
- It was a critical voltage day
  - Voltages were within limits and operators had taken actions to boost voltages
- The frequency was typical for a summer day
- The power system was within operational limits prior to 15:05, on both actual and contingency basis

The blackout was a typical mixture between voltage and frequency problems. The loss of Eastlake 5, at 13:31 Eastern Daylight Time (EDT) due to reactive power control issues (see Figure 15), was a significant contributor to the outage later in the afternoon. The trip of Eastlake 5 caused the loading on several transmission lines to increase, but still well within normal ratings. Due to poor tree trimming, the trees hit the conductors of lines that were far from overloaded, which caused a first line to trip. The remaining lines were then more heavily loaded and came in contact with non-trimmed trees, and so on for a number of lines. The line trips caused low voltages and an increased need for reactive power, which caused some generator units to trip on excitation related protection criteria. This caused a mismatch in generation and load, and finally the frequency became so low that the automatic load shedding system was triggered, which caused a high frequency and trip of generation, and so on. The disturbance was sequentially developed with trips and intermediate stabilization.

The root cause of the disturbance was the poor tree trimming. Lack of observation possibilities, poor communication between the different areas and operators, and poor software, worsened the situation.

Figure 15 shows the Eastlake 5 excitation failure trip, that started the sequence of events that led to the blackout. Normally a current limiter should have limited the field (or stator) current, and kept the reactive power output close to, but below, the 'Rated MVAr Limit'. The coordination between current limiters and protection (causing a unit trip) was the main finding from the Western France disturbance in 1987 /14/.

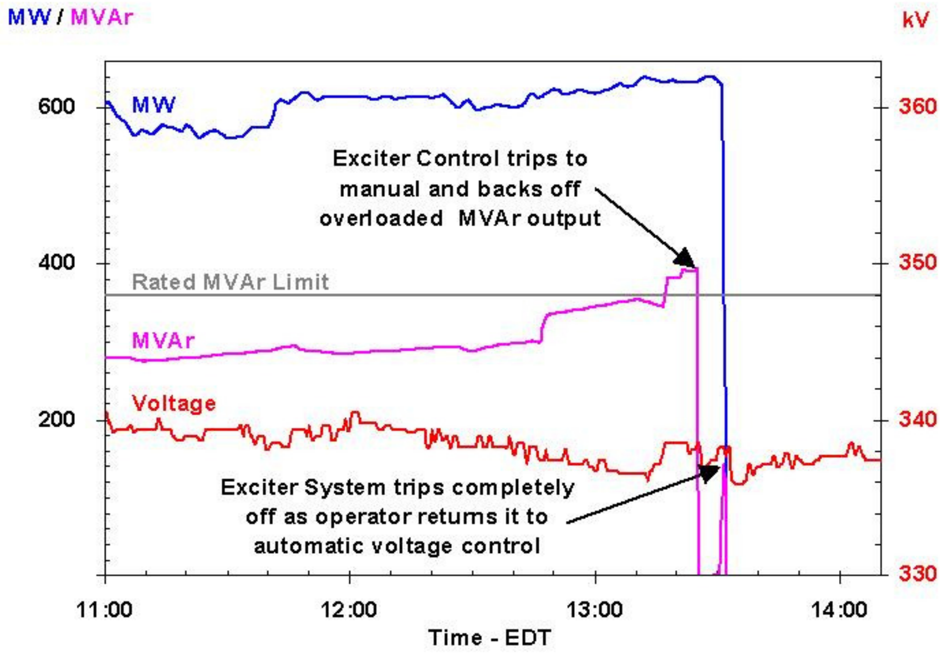


Figure 15: East Lake 5 exciter causes the trip of the unit /13/

As lines are tripped due to ground faults and the load is increasing on the remaining lines, the voltages are decreasing and the currents are increasing, causing the line impedance measured by the distance protection, to decrease and potentially to enter into zone 3. A number of such zone 3 trips were experienced, see e.g., Figure 16. This experience caused a big discussion about the zone 3 utilization in transmission systems with Main1 and Main2 protection, breaker failure protection and busbar protection. Some TSOs take the zone 3 out of service, while others have the same settings for both zone 2 and zone 3.

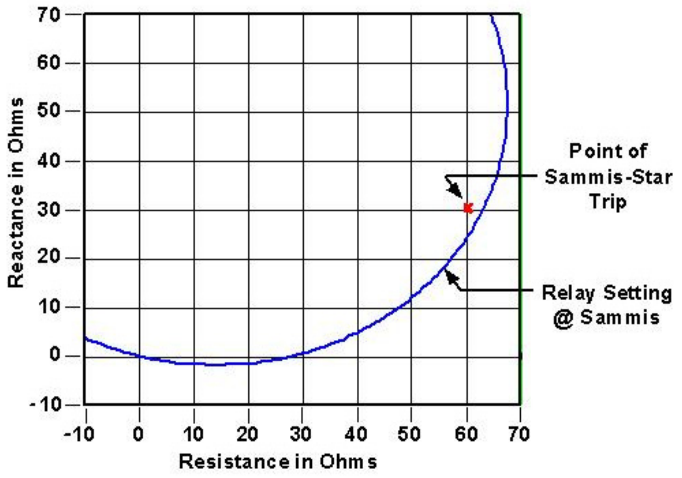


Figure 16: Sammis-Star zone 3 relay operates /13/

An example of voltage decaying, due to line trips and load recovering during the disturbance is shown in Figure 17.

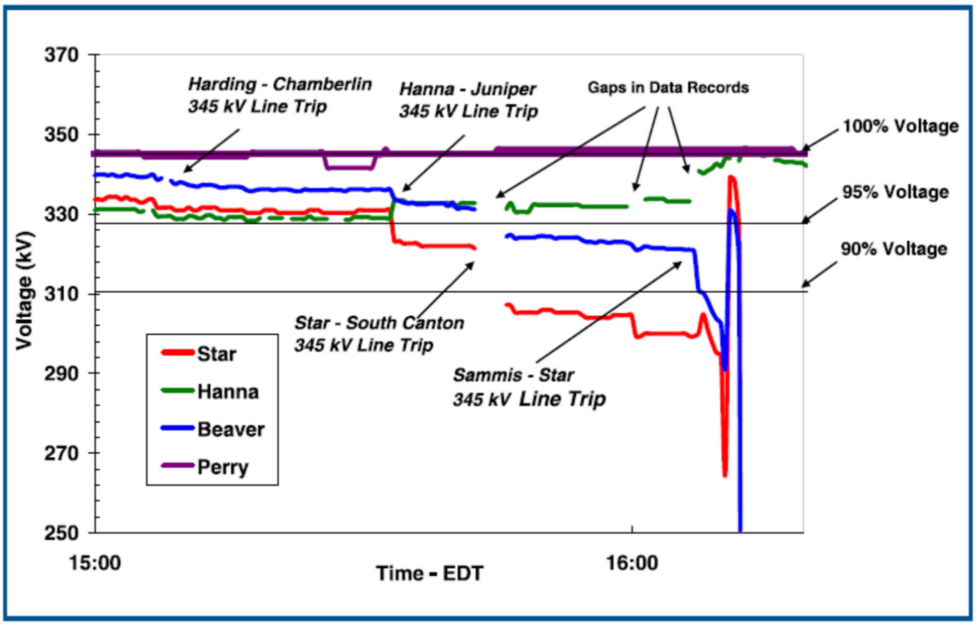


Figure 17: Voltages on FirstEnergy's 345 kV lines and the low voltage impact on line trips /13/

At 16:10:49 EDT automatic under-frequency load shedding was initiated in Ontario since the frequency declined below 59.3 Hz. Two hydro units were isolated to the Western New York island and the surplus in generation together with the load shedding resulted in a frequency of up to 63.4 Hz for the island. Consequently, five of the U.S. nuclear units within the island tripped due to overfrequency.

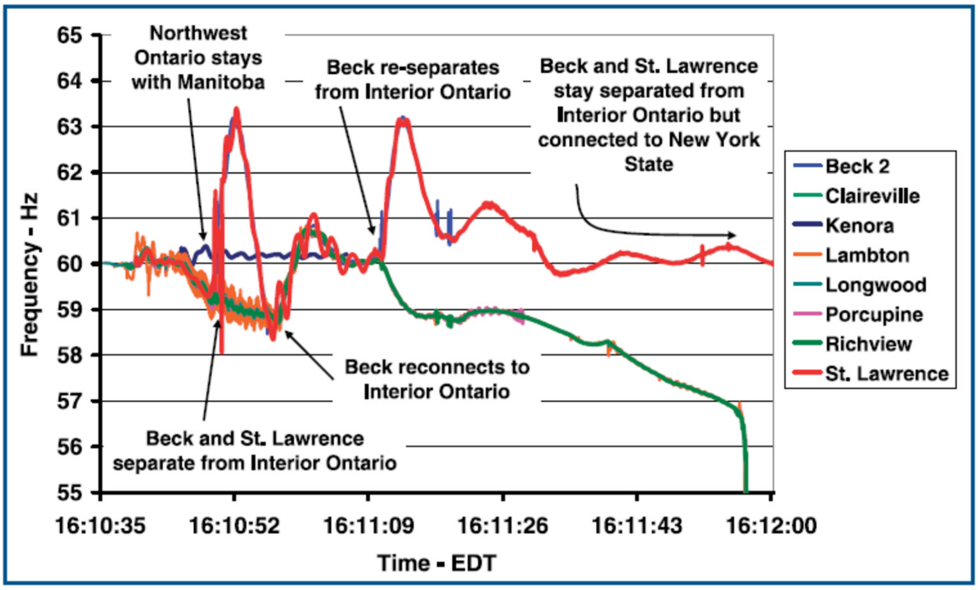


Figure 18 Frequency separation between Ontario and Western New York /13/

The normal and abnormal frequency ranges are described in Figure 19.

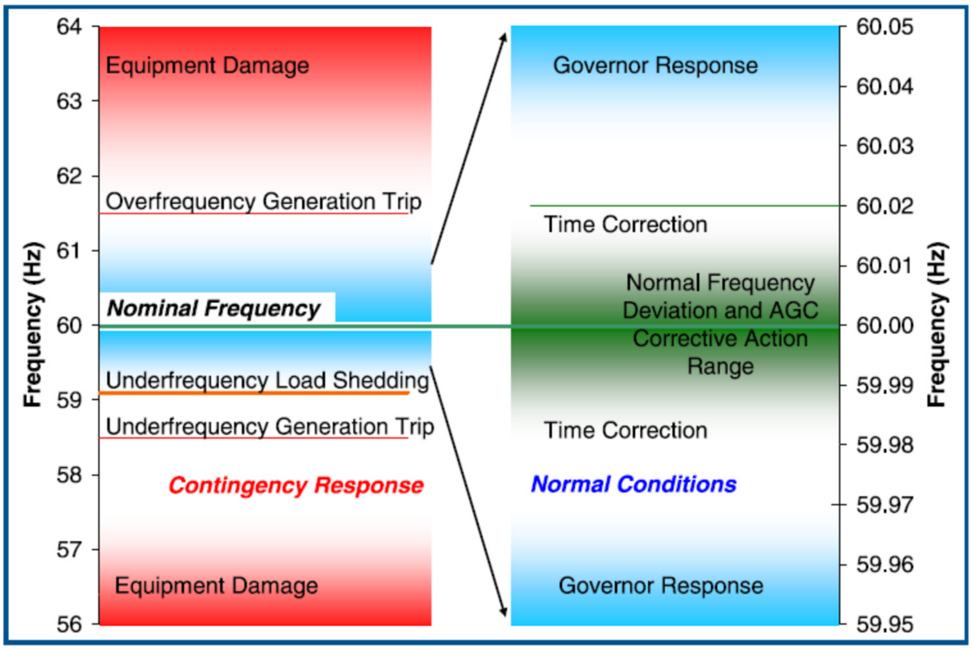


Figure 19 Normal and abnormal frequency ranges in the U.S Canada system /13/

In the Final report from the task Force /13/ an entire section is dedicated to the "performance of nuclear power plants affected by the blackout". Reading this section, it is clear that the disturbance escalated and stabilized a number of times before the final breakdown. Nine US nuclear power plants experienced rapid shutdowns (reactor trips), within about 60 seconds, as a consequence of the grid disturbance. Many other nuclear power plants experienced a transient due to the grid disturbance. Seven nuclear power plants in Canada operating at high power levels at the time of the event also experienced rapid shutdowns. Four other Canadian nuclear plants automatically disconnected from the grid due to electrical transients, but were able to continue operating at a reduced power levels. Six nuclear plants in the United States and one in Canada experienced significant electrical disturbances but were able to remain grid connected and continue power generation. Several other nuclear plants observed disturbances on the grid but continued their generation without interruption.

It is clearly stated in the report that

- The affected nuclear power plants did not trigger the power outage or inappropriately contributed to its spread (except the expected tripping of the plants at expected conditions).
- The nuclear plants responded to the grid conditions in a manner consistent with the plant designs.
- Trend data obtained indicate stable conditions until a few minutes before the event.

Reading further into the details of the report, the tripping details are presented for each nuclear unit.

In the US some units tripped due to main generator trips, which resulted from voltage and/or frequency fluctuations on the grid. Some units tripped due to initial nuclear reactor trips, due to frequency fluctuations on the internal grid or low frequency, which caused internal issues in the NPP, such as low turbine control system pressure or tripped reactor coolant pumps. All nine plants that experienced a reactor trip were responding to grid conditions in a manner consistent with the plant design. It can be noted that, the re-synchronization times of the US NPPs could have been much shorter had the NPPs had the capability of house load operation.

In Canada, frequency and/or voltage fluctuations on the grid resulted in the automatic disconnection of some generators from the grid. Load swing on the grid led to automatic disconnection of four generators.

Trip Criteria and Grid Conditions

Below the tripping relays, trip criteria and grid conditions for the different nuclear plants are summarized

- Generator field protection (overexcitation (V/Hz) and loss of field)
- Large Mvar swings
- Load rejection
- Low pressure in the hydraulic system that controls the turbine valves
- Grid frequency fluctuations and underfrequency
- Significant overvoltages and undervoltages on the grid
- High reactor temperature
- Auxiliary bus frequency fluctuations that tripped reactor coolant pumps
- Turbine trip on light load protection, reverse power after reactor trip
- High temperature, due to loss of cooling, due to loss of power to pumps
- Large voltage oscillations and loss of excitation
- Power mismatch between reactor and turbine

US Details

Some nuclear power plants tripped as a result of voltage issues. For example, at Fermi 2 a generator field protection tripped as voltage regulators tried to compensate reactive power fluctuations. Another example is Oyster Creek, which experienced a generator trip triggered by the high voltage to frequency ratio.

Other nuclear power plants tripped as a result of frequency issues. For example, at Indian Point 2, Indian Point 3, and Perry underfrequency relays were activated. In other cases, the frequency went higher than normal, and turbine control systems reacted to control the frequency. As a results of that, equipment limits were exceeded at Fitz Patrick, Nine Mile 1, Nine Mile 2, and Ginna.

Canada Details

Two nuclear power plants, Bruce B and Pickering B, tripped due to frequency and/or voltage fluctuations. At Darlington, the power output was initially reduced due to load swings of the grid and then automatically disconnected from the grid.

Point Lepreau was affected by the disturbance but did not trip. Instead, the output dropped by 140 MW in response to the changing grid frequency. The reactor power remained constant with the excess thermal power being discharged through the steam discharge valved. During the course of events, speed oscillations were dampened by the unit stabilizer (PSS).

3.6.2 Conclusions and lessons learned

This was a complex slowly escalating disturbance, including both frequency and voltage issues. The main conclusions and lessons learned from the 2003 US Canada disturbance are:

1. Tree trimming is essential and must be maintained (line trip due to inappropriate tree trimming has been experienced in Sweden too).
2. Software systems must be up to date and regularly tested.
3. Operational situation observations from neighboring areas must be exchanged.
4. Increased efforts must be put in systems for "early warnings". So called situation awareness systems, must be installed, maintained, and used. Such systems are very often based on PMUs, data concentrators, and software for visualization and alarms. The North American SynchroPhasor Initiative (NASPI) is a result from this disturbance and is still active (https://www.naspi.org).
5. It is stated in the investigation report that 'Trend data obtained indicate stable conditions until a few minutes before the event'.
   - One minute is plenty of time for properly designed remedial action schemes to handle voltage and frequency issues to maintain the energization and preserve the integrity of the transmission grid.
6. The settings of the protection (causing trip) and the limiters (causing output limitation) must be coordinated, in such a way that the output can be efficiently limited, without a unit trip.
7. In general, the settings of the units must be set with respect to the applicable *grid connection regulations*, however, it might be beneficial for the system if the

settings are set with respect to the *unit capability*, which must be equal to or better than the formal requirements. This is an interesting discussion between risk and remuneration to find the optimal settings for the units from a system perspective.

3.7 UNDERFREQUENCY EVENT LONDON (2019)

On Friday the 9th of August 2019 the electricity system was operating as usual. The weather was normal for the time of the year with heavy rain, lightning storms, wind and high temperatures. At 16.52 a lightning strike occurred on the Eaton Socon – Wymondley transmission line which was cleared correctly by the line protection system. As expected, when lightning strikes a transmission line, there was a loss of approximately 150 MW embedded generation due to vector shift protection. However, both Hornsea offshore windfarm and Little Barford power station steam turbine unexpectedly reduced their power by 737 MW and 244 MW respectively.

The sudden loss of 1 131 MW of generation led to a fall in frequency which caused a further 350 MW of generation to disconnect. The total lost generation was now 1 481 MW which was more than the 1 000 MW secured automatic "backup" power that had responded to the frequency drop. The frequency fell quickly to 49.1 Hz, and just as it was recovering with all available tools and backup powers, another gas turbine at 210 MW at Little Barford Power Station tripped due to a bypass valve not being able to operate correctly. The total generation loss was now 1 691 MW and the frequency fell to 48.8 Hz, where secondary backup systems automatically disconnect loads.

Due to the low frequency, the second gas turbine at 187 MW at Little Barford tripped, which took the cumulative loss of generation to 1 878 MW. The underfrequency controlled load shedding scheme disconnected customers in a controlled way and approximately 1000 MW of the Great Brittan was disconnected. Approximately 1.1 million customers were without power for 15-45 minutes, and there were major disruptions to the rail services. Processes and protocols have been reviewed in order to mitigate the risk for something similar to happen in the future. /15/

The trip of the Hornsea is chosen for deeper investigation, since Hornsea represents the very interesting AC connected offshore renewable generation, based on converter connection. This is an excellent disturbance to learn how AC connected offshore windfarms might react to "normal" contingencies in the connecting grid.
The low frequency situation is, however, well covered by other low frequency incidents, such as Zeeland and Southern Sweden (2003) and the Continental Europe system separation 2006, discussed in Section 3.4 and Section 3.8 respectively.

3.7.1 Deeper Investigation of the Hornsea response

The main part of this deeper investigation is based on the technical report from National Grid ESO /15/.

The overall sequence of events is summarized in Figure 20, as a function of the system frequency. Hornsea trips at 737 MW in the beginning of the disturbance, due to the voltage transient introduced by the primary fault, at a frequency close to the nominal frequency of 50 Hz.

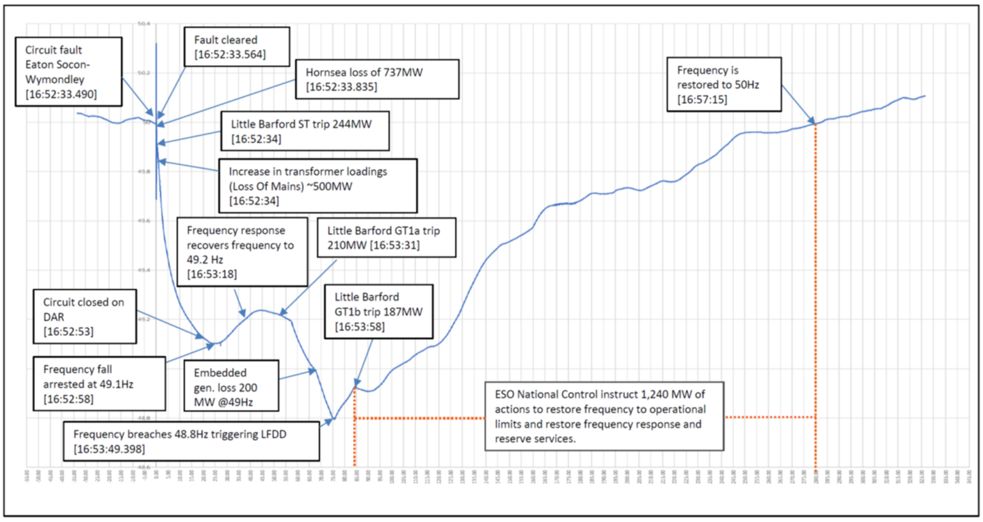


Figure 20 Annotated frequency trace of the event, August 08, 2019. /15/

Hornsea is the largest offshore windfarm in the world, comprising 174 turbines of 7 MW each, located 120 km from shore, and owned by Orsted. The project features the world's longest high voltage AC offshore wind export cable system, comprised of more than 900 km of cables, including a 190 km 220 kV AC cable, which transfers the generated electricity to the shore and national grid. The wind farm includes three offshore wind generating stations, two offshore accommodation platforms, up to two offshore HVDC converter stations, an offshore HVAC reactive compensation substation, and five HVAC collector substations, which are connected through inter array cables of 30 to 70 kV. In summary, a very complex and vulnerable AC connection system, including active filtering in a large-scale STATCOM for the integration of the Hornsea offshore power.

Following the lightning strike (and clearance of the fault) on the Eaton Socon-Wymondley circuit, Hornsea immediately de-loaded from 799 MW to 62 MW. The timing and magnitude of the active power reduction are shown in Figure 21. The response of Hornsea offshore wind farm was unexpected, and a breach of grid code requirements. It is unacceptable that generation is tripped due to a properly cleared transmission line fault (unless it is a fault on a radial connection line). The wind farm owner, Orsted, presented an explanation to the unexpected de-loading behavior that reveals the complexity and lack of experience with the control systems of renewable generation Orsted claimed that Hornsea has been corrected to comply with all grid code requirements.

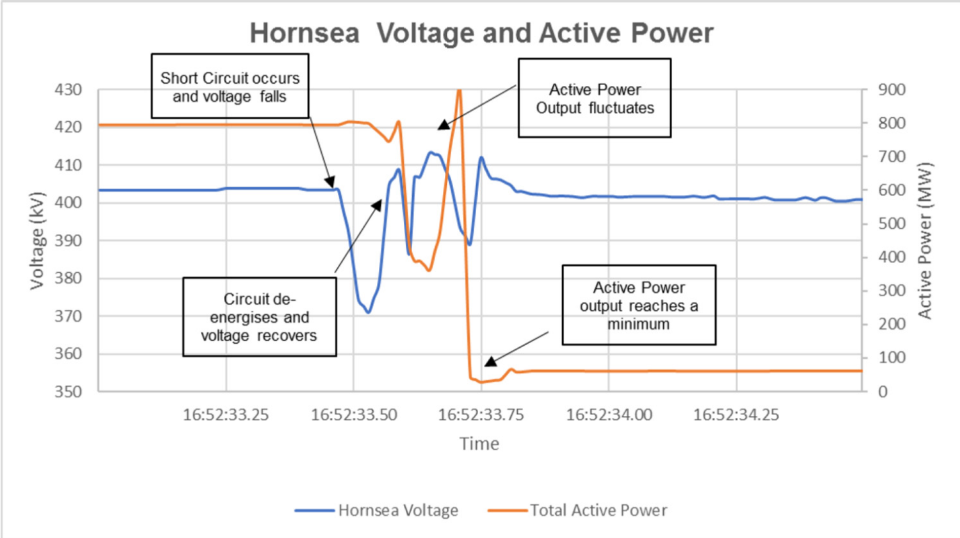


Figure 21 Voltage and active power at the Hornsea 400 kV onshore connection point /15/

Hornsea has confirmed that a system voltage fluctuation was seen at the onshore connection point coincident with the fault and fault clearance. The reaction to the voltage dip resulting from the fault by Hornsea's control systems was as expected in attempt to accommodate and address the system condition. We can see this response in Figure 22.

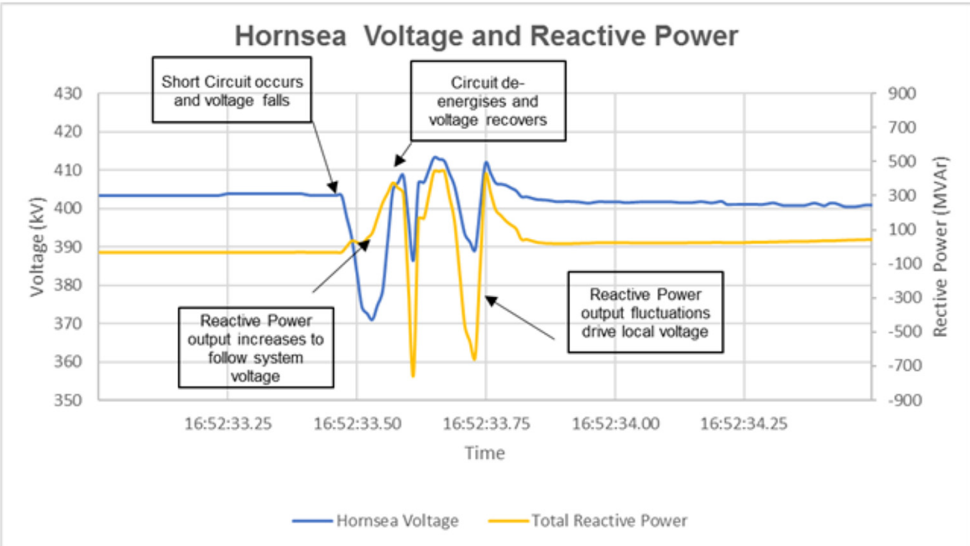


Figure 22 Voltage and reactive power at the Hornsea 400 kV onshore connection point /15/

However, very shortly afterwards when the transmission system voltage recovered on clearance of the short circuit, as shown in the figures above, the reaction of Hornsea wind farm as seen at the onshore connection point showed unexpected large swings in active power and reactive power which should not have occurred. Similar large swings are seen in data recorded at the offshore wind farm.

Orsted has carried out an investigation and provided a Hornsea Technical Report which advises the following:

Initially, Orsted understood that the dynamic reactive compensator was responsible for the rapid de-load of Hornsea. The configuration of the Hornsea network, with one super grid transformer and one offshore transmission system user asset on outage, was a contributory factor as it created a weak internal network environment. Subsequently, Orsted has reviewed and reconfigured its network. The original wind turbine settings were standard settings from the manufacturer. During the incident, the turbine controllers reacted incorrectly due to an insufficiently damped electrical resonance in the subsynchronous frequency range, so that the local Hornsea voltage dropped, and the turbines shut themselves down. Orsted has updated the control system software for the wind turbines and has observed that the behavior of the turbines now demonstrates a stable control system that will withstand any future events in line with the applicable Grid Code and Connection and Use of System Code (CUSC) requirements.

3.7.2 Conclusions and lessons learned

The triggering event of this disturbance was a simple lightning strike to a transmission line that was properly cleared. The loss of embedded generation due to vector shift relays was expected, but the subsequent loss of generation at Little Barford (nearby) and Hornsea, remote, was unacceptable. The main conclusions and lessons learned from this disturbance are:

1. The generation connection regulations, such as ENTSO-E RfG and national regulations, must be followed, tested, and documented. It is totally unacceptable that a generator trips or reduces its power output due to a properly cleared line fault.
2. The performance of converter connected generation and especially the response to power system transients must be thoroughly tested and verified.
3. Be careful with long highly compensated high voltage AC underground or subsea systems.
4. Do not include subway, metro, trams, elevators, and other sensitive load objects where people are “locked in”, in the underfrequency controlled load shedding schemes.

3.8 SEPARATION OF CONTINENTAL EUROPE (2006)

A ferry boat requested a double circuit line outage for safe passing, which resulted in line overload at other locations and cascaded line trips that led to system separation. The resulting frequency excursions were significant.

The effects on the exposed NPPs with respect to the high and low frequency resulting from the system separation, are chosen for deeper investigation.

3.8.1 Deeper Investigation

The main part of this deeper investigation is based on the UCTE report /16/.

In September 2006, E.ON Netz made preparation for a request from a shipyard to disconnect the double circuit 380 kV line Conneforde-Diele on 5 November at

01:00. This type of switching was not out of the ordinary and had been performed many times before.

Two days before the planned disconnection, the shipyard asked E.ON Netz to change the time of the disconnection to three hours earlier. E.ON Netz agreed but neighboring TSOS, RWE and TenneT, were not informed of the change until a couple of hours before the actual disconnection.

It has to be kept in mind that the day-to-day grid operation had become much more challenging than before, due to volatile wind infeed and hourly changing trade volume of thousands of Megawatts. The system had more often to be operated closer to its limits, which was also the case on November 4. There was a high power flow from Germany to The Netherlands and to Poland due to the high wind generation in Germany, in the evening of November 4th.

The change in time of the planned disconnection was made too late for any reduction in the exchange program between Germany and The Netherlands to be made, as had been the original plan.

TenneT informed E.ON Netz that the flows between Germany and the Netherlands were high half an hour before the disconnection but both TenneT and RWE agreed to the disconnection of the Conneforde-Diele double circuit line.

Detailed sequence of events leading to UCTE system splitting

E.ON Netz switched off the Conneforde-Diele double circuit line at 21:39 and received warning messages about high power flows on other lines. At 22:10 RWE reached out to E.ON Netz to ask for urgent intervention due to overload on the Landesbergen-Wehrendorf line. In response, E.ON Netz coupled the busbars in the Landesbergen substation, expecting it to reduce the current by 80 A. This decision was an empirical assessment and no load-flow calculations were made to check the N-1 criterion.

In the post-event analysis, simulations showed that this action had the opposite effect and the current was increased by 67 A causing the line to trip due to overload. Figure 4 shows the flow on of the Landesbergen-Wehrendorf line. It clearly shows the increase at the time of the disconnection of the Conneforde-Diele double circuit, the gradual increase that followed and the immediate trip at the time of the coupling of busbars in the Landesbergen substation. Once this line had tripped, there was a series of cascading line trips throughout the UCTE area. All lines tripped by distance protection, due to overloading.

The need of re-dispatching was not evident to E.ON Netz immediately after the Conneforde-Diele double circuit was disconnected, and once the cascade of line trips started, any re-dispatching to stabilize the grid would have taken too long.

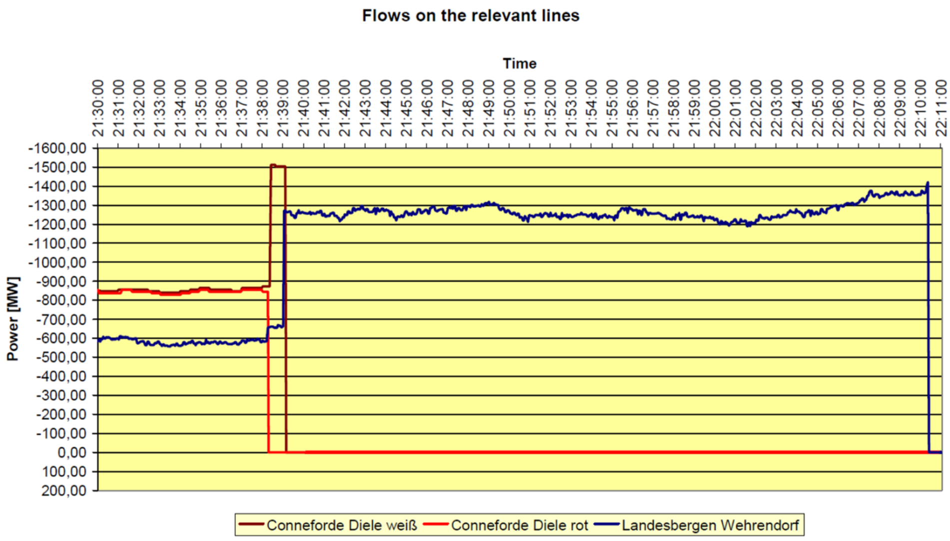


Figure 23 Power flow on the Landesbergen-Wehrendorf line before and after Conneforde-Diele switching off /16/

The UCTE system was split into three areas at 22:10:28, see Figure 24 and Figure 25.

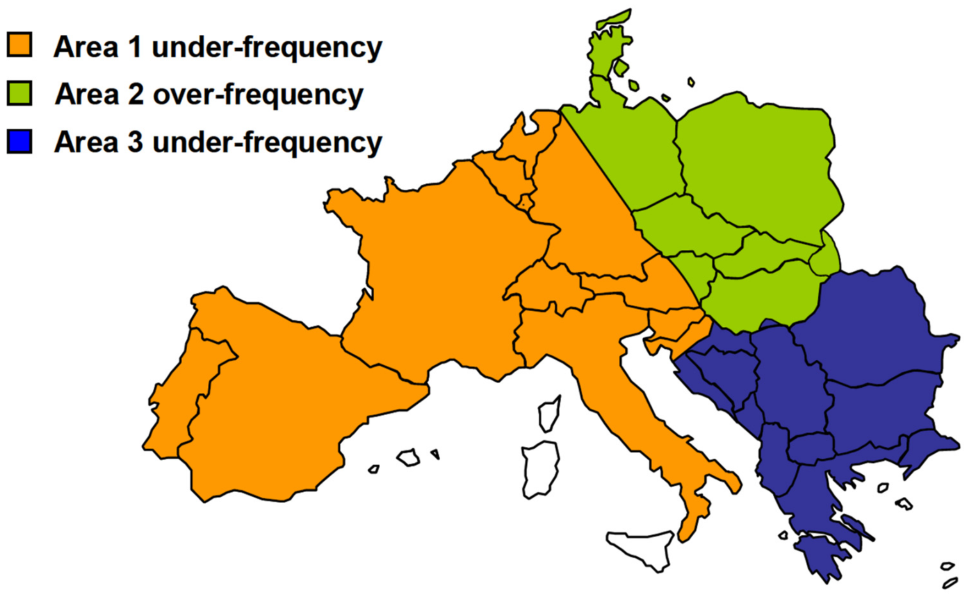


Figure 24 Schematic map of the UCTE area split into three areas /16/

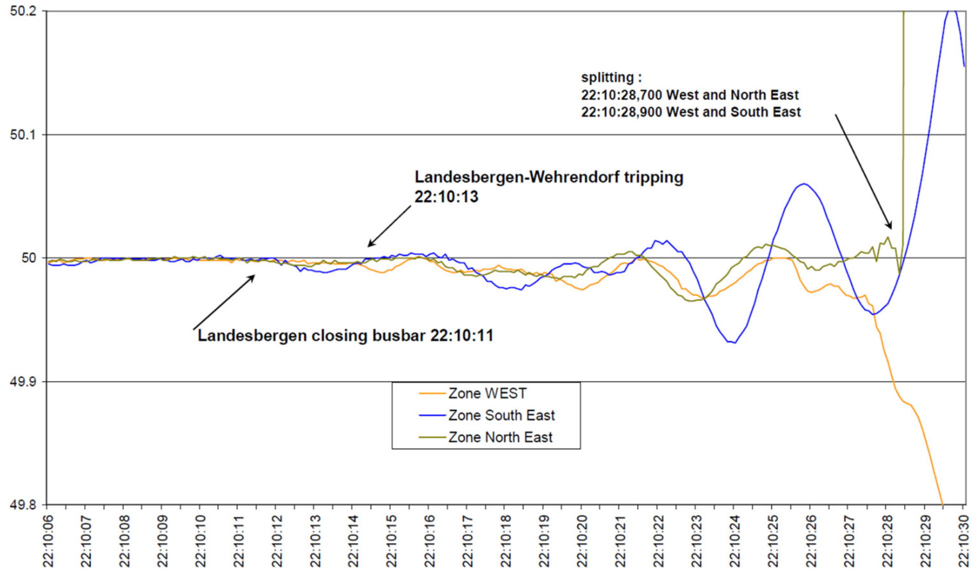


Figure 25 Frequency recordings for the area split /16/

In Figure 26 the frequencies of the three separated areas are shown for a longer time period than in Figure 25. The frequency excursions are considerable, especially in the Western area. The frequency of the Northeastern area, clearly shows the importance of not having the overfrequency trip of all (or most of) the generators set at the same level, which is very relevant also for Nordic conditions.

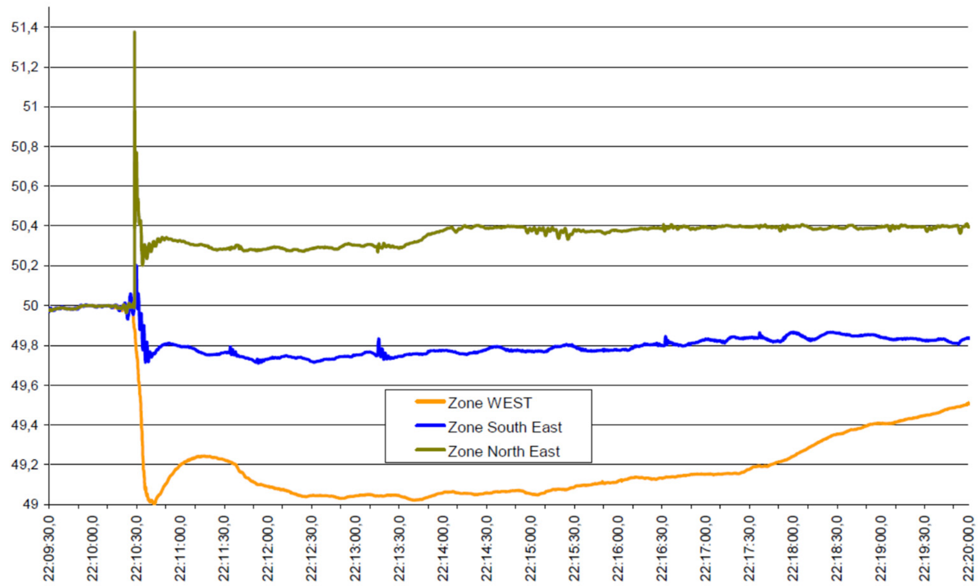


Figure 26 Frequency recordings retrieved by Wide Area Measurement Systems (WAMS) after the split /16/

The UCTE report /16/ does not include much information about the response of the nuclear units in the different areas, due to the significant frequency excursions. It is only mentioned that nuclear units were unable to re-dispatch (before the event) since they were already operating with maximum output.

The IAEA report /17/ however, addresses the issue of power system frequency control support from nuclear units. The German and French operating experience are described in Annex I and II to the IAEA report. The goals of the improved programs in France were to accomplish rapid load following (from 100% rated thermal power (RTP) to 30% RTP), frequency control (±7% RTP) and rapid (up to 5% RTP/min) return to full power. Frequency related ancillary services from nuclear units is becoming more and more interesting, especially for the Nordic system with an increasing amount of intermittent generation.

3.8.2 Conclusions and lessons learned

The main conclusions and lessons learned from this disturbance are listed below:

1. Generation pattern based on wind might change significantly within a short time period, which has to be carefully taken into account for outage planning, and especially in situations with short notice outage re-scheduling.
2. Communication and information exchange between different system operators is (as always) important.
3. The observability of nearby systems and real time power system situation awareness is important, for every system operator.
4. System separation at high power exchange levels will result in large frequency excursions, and especially low frequency areas might be problematic.
5. For high frequency areas, overfrequency triggered trip of generation must be coordinated in such a way that all (or many) generators are not tripped at the same time (or at the same frequency level). Such a dispersed setting philosophy is also valid for any frequency derivative triggered tripping function.
6. Nuclear power plant frequency control support would be beneficial.
7. Increased renewables integration, with converter connected generation, results in less inertia in the power system. Thus, the significant inertia from the nuclear units is very much needed.
8. Using zone 3 of the distance relays as overload protection is not advisable. Zone 3 should be exclusively regarded as a delayed primary fault protection, or, if significant redundance is achieved in other ways, not to be used.

3.9 UKRAINE CYBER ATTACK (2015)

On 23 December 2015, a first-of-its-kind cyber-attack on a power system was experienced. The power supply in Western Ukraine was switched off by hackers also sabotaging power distribution equipment and complicating attempts to restore power.

The root cause, i.e. the cyber-attack, as such is chosen for deeper investigation, while the consequences of the breaker trips are covered by other disturbances in this report.

3.9.1 Deeper Investigation

This deeper investigation is primarily based on the article and the report /19/.

Hackers performed a remote and coordinated attack on three regional power distribution companies in the Ukraine resulting in power outages. Out of the three, Prykarpattyaoblenergo was affected the most with around 30 substations, on 110 and 35 kV, taken offline, resulting in about 230 000 people being without electricity for up to 6 hours. The other two power distribution companies were affected at a smaller scale. Three other infrastructure organizations were also compromised but without any impact on their operations.

It has been argued /20/ that 'Ukraine was a special case, comprising unusually dilapidated infrastructure, a high level of corruption, a military conflict with Russia, and exceptional possibilities for Russian infiltration due to the historical linkages between the two countries'.

The cyberattack consisted of the following steps /18/:

- Spear-phishing campaign, months before the coordinated attack, targeting IT staff and system administrators at power distribution companies
- Over many months worker credentials for VPN access to the SCADA systems were retrieved
- The backup power to two control centers were reconfigured
- On December 23rd, hackers entered the SCADA systems through the retrieved VPNs and opened breakers
- Just before opening the breakers, a denial-of-service attack was launched against customer call centers to deny consumers up-to-date information on the blackout
- Legitimate firmware was replaced with malicious firmware at substations to prevent operators from sending remote commands
- Operator stations were rendered inoperable as malware caused computers to crash

3.9.2 Conclusions and lessons learned

This is a totally new area of power system interference, where the electrical power sector has limited experience. The main conclusions are listed below.

1. Care with respect to cyber security has to be emphasized.
2. Lessons must be learned also from other fields and society infrastructures, as well as attacks experienced.

3.10 LOSS OF NORDLINK HVDC CONNECTION 2022-01-02

This disturbance is interesting since the NordLink was almost fully loaded and caused a rather deep frequency dip. The number of HVDC links of this size is increasing in the Nordic system, and thus this type of frequency deviations will become more frequent. Therefore, the disturbance is selected for deeper investigations.

3.10.1 Deeper investigation of the trip of NordLink HVDC 2022-01-02

The main part of this deeper investigation is based on material provided by Svenska kraftnät /22/.

On Sunday 2022-01-02 at 00:14, the NordLink HVDC connection between Norway and Germany tripped at 1317 MW import to Norway. The specific reason for the trip is not yet known.

A frequency recording from a DNV PMU, connected to the low voltage system in Southern Sweden and operated by a voluntary subcontractor[1], is shown in Figure 27. The lower part of Figure 27 clearly shows a high frequency ripple in the frequency signal.

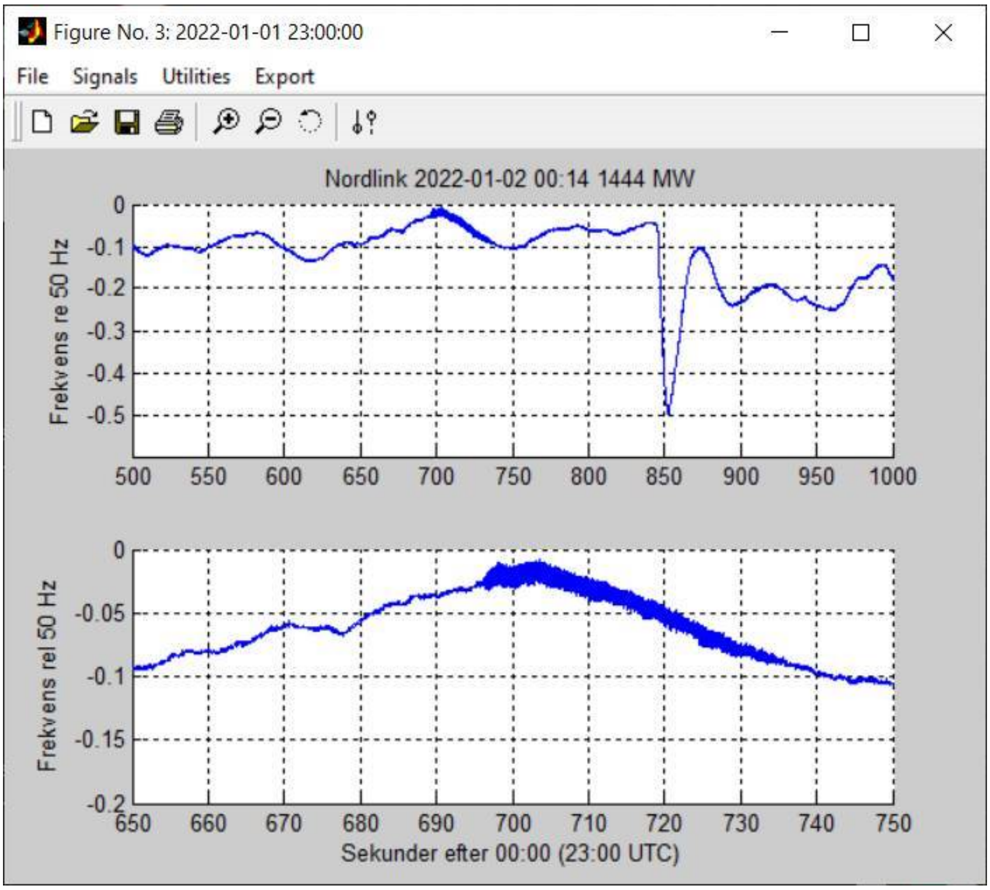


Figure 27 Frequency deviation in Southern Sweden following the NordLink trip, as a function of seconds after midnight (1444 MW is the total unavailable power capacity of the link)

The minimum frequency was registered to 49.5 Hz. A deeper analysis performed at Lund University /21/, shows that this is a superimposed 11 Hz ripple, see Figure 28. The frequency goes below 49.8 Hz during at least five occasions. The frequency stays below 49.8 Hz for 16, 26, and 46 seconds for the three first occasions.

Some hydro power units in Norway tripped due to the low frequency. Probably more than 2000 MW of generation, including NordLink, was tripped, and low voltages were observed in different parts of the grid, one end of a series compensated 400 kV line was down to 373 kV and a thermal power plant in Sweden was tripped. Emergency power (EPC) of 150 MW on one of the HVDC

[1] Göran Runvik, local power producer and PMU manager Southern Sweden

links was activated. In total seven gas turbines were automatically started in Sweden. The voltage decay was quickly re-established.

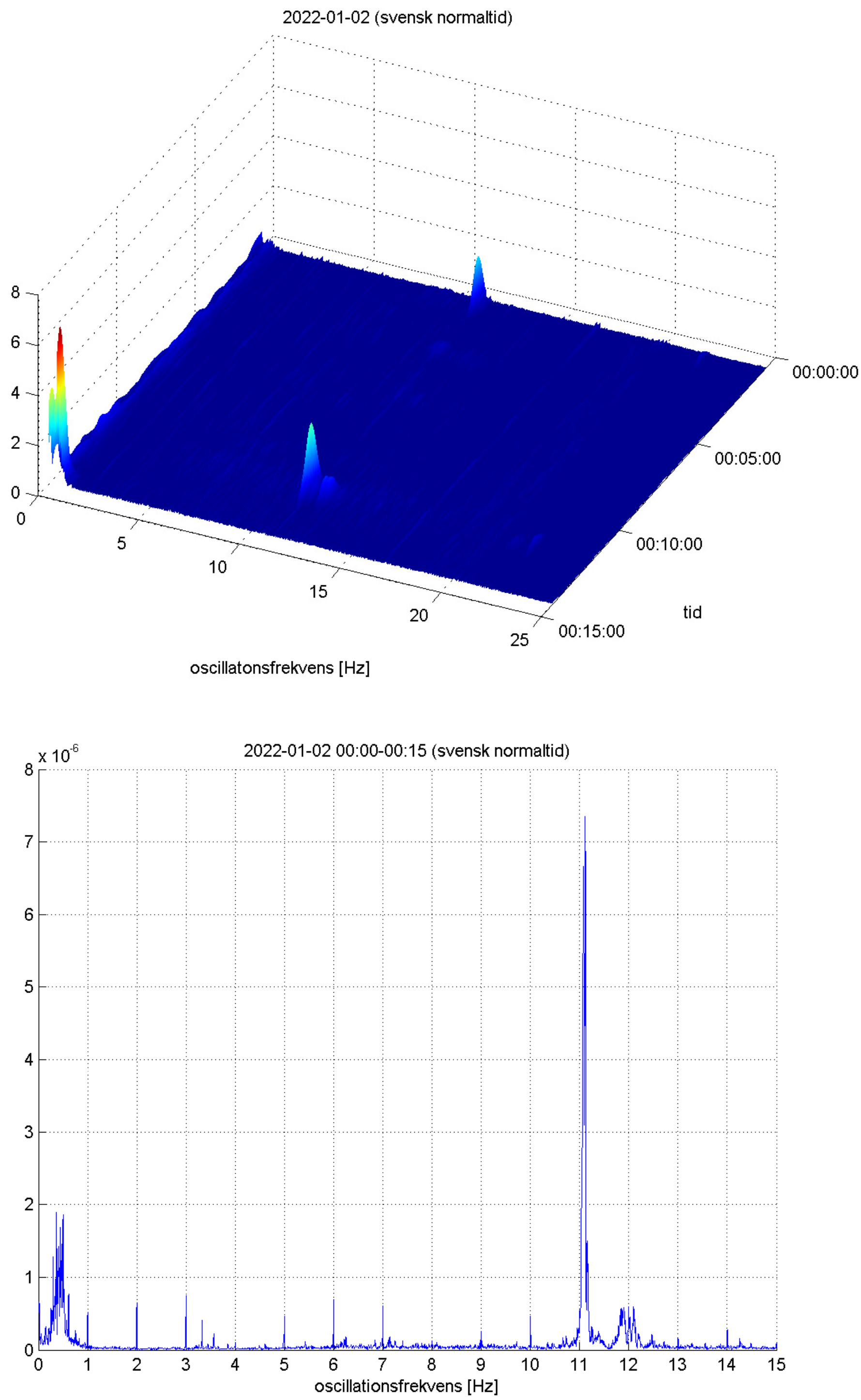


Figure 28 Oscillation frequency spectrum of the "frequency signal" immediately before the NordLink trip /21/

The frequency spectrum is derived from the frequency difference between Southern Sweden and Tampere in Finland (where the 11 Hz interference was not visible), see Figure 29. The source of the 11 Hz superimposed signal is not yet known. Similar abnormal signals have been observed also at other occasions.

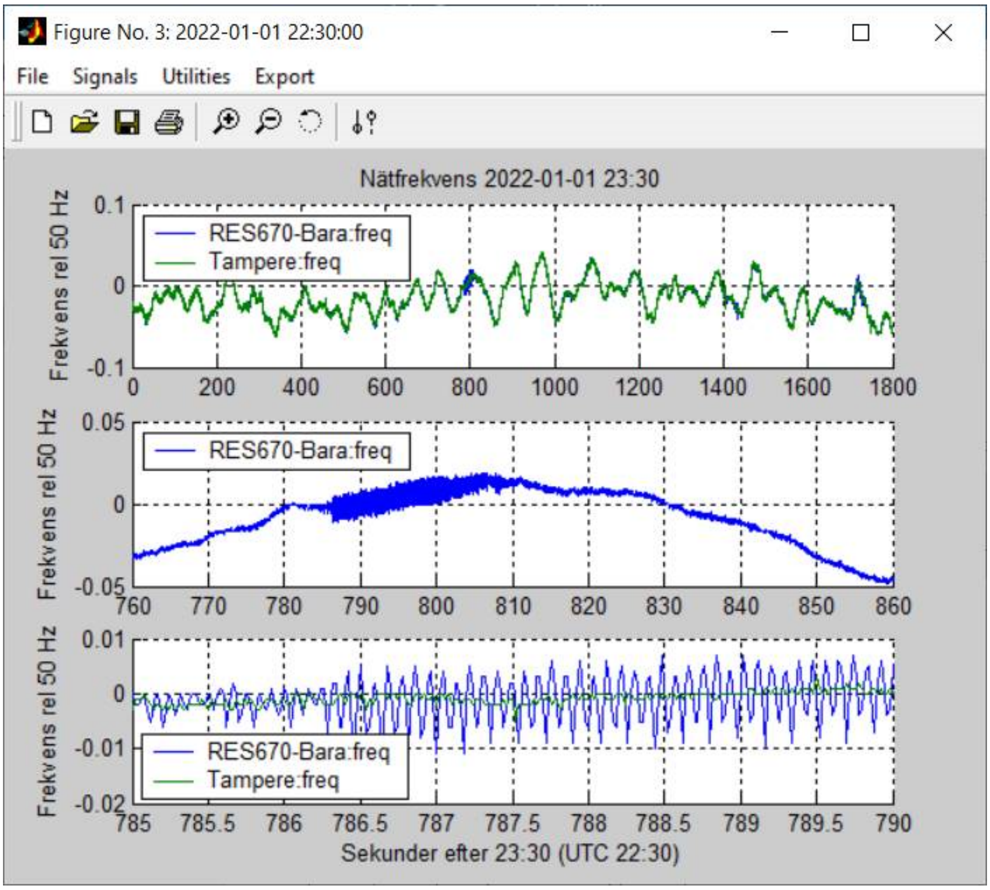


Figure 29 The frequency as measured by PMUs in Tampere and in Southern Sweden. /21/

3.10.2 Conclusions and lessons learned

The power import of the tripped HVDC connection analyzed is close to the dimensioning loss of a single source of power infeed in the Nordic system. The frequency drop, down to 49.5 Hz, for such a big loss in the middle of the night is as such not alarming, but a number of remedial actions were triggered such as HVDC EPC and gas turbine startups. The rotational energy of the Nordic system at the time for the disturbance was estimated to about 200 GWs[2]. The main conclusions and lessons learned are listed below.

1. The loss of a single HVDC connection is similar to the loss of a large generator or load. The HVDC converter power electronics might be more vulnerable to grid transients, and thus there might be a larger risk for trip of more than one HVDC connection from the same triggering network disturbance. Such a

[2] Inertia of the Nordic power system - Fingrid

course of events could be comparable to the underfrequency event in London 2019, as described in Section 3.7, where two generation units tripped due to a properly cleared line fault.

2. Non-dimensional (worse than N-1) loss of generation happens once a decade or so. The HVDC links seem to have a higher failure rate than conventional generation of similar size. With the increasing amount of HVDC links and large sized converter connected generation, the rate of non-dimensional power infeed trips might increase.
3. Unexpected things might happen, such as the temporary superimposed 11 Hz regional oscillation mode. This 11 Hz mode should preferably be further investigated, especially with respect to origin, possible consequences, and the potential for similar oscillations.

3.11 LOSS OF SEVERAL UNITS IN LULE RIVER 2005-12-01

A rather simple primary root cause in terms of one stuck breaker pole, caused a cascade of trips and a final system separation, with a significant non-credible loss of generation and frequency decay. Although, transmission system busbars and switchgear design has been improved since the Lule River incident, other common cause for loss of generation failures might show up. Therefore, this event is chosen for a deeper investigation.

3.11.1 Deeper investigation of the Loss of Several Units in Lule river 2005-12-01

The main part of this deeper investigation is based on material provided by Svenska kraftnät /22/.

To compare with the disturbance of January 2, 2022, one of the most severe loss of generation disturbances experienced in the Nordic system, the disconnection of several units in Lule River 2005-12-01 is revisited below. Figure 30 shows the frequency in the system and the phase angle difference between Luleå and Lund before and after the loss of the generation. The frequency recovers quite quickly, while replacement generation in Southern Sweden (gas turbines) keeps the phase angle difference low for more than an hour.

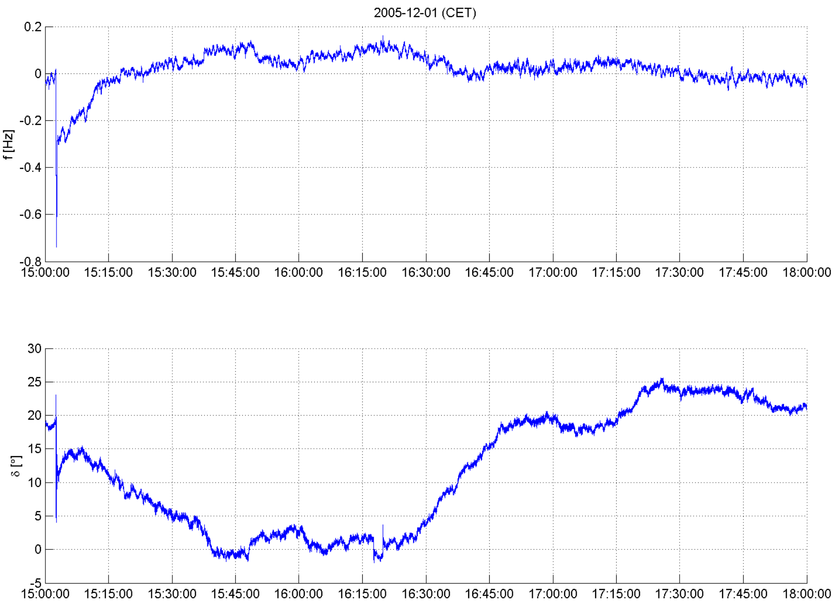


Figure 30 Frequency and phase angle difference between Luleå and Lund. /21/

The minimum frequency was measured to 49.26 Hz and the details of the frequency dip are shown in Figure 31.

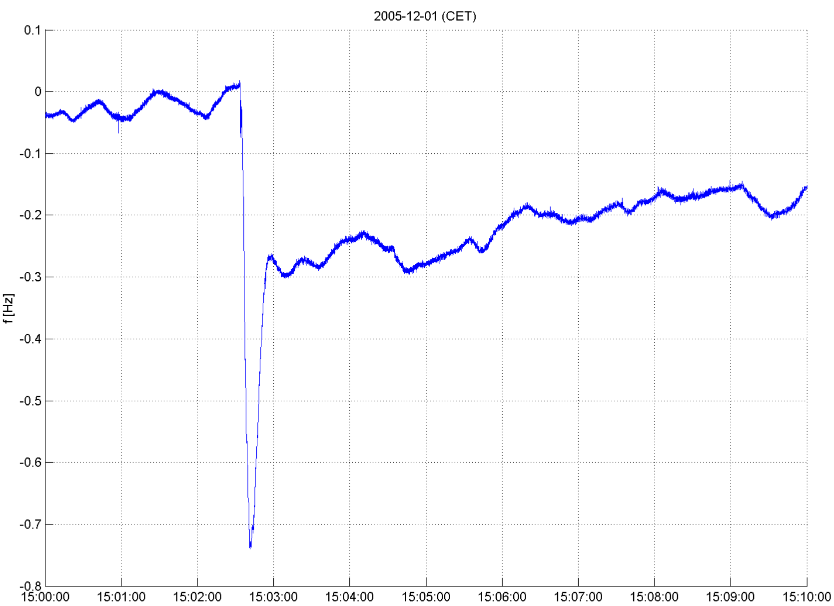


Figure 31 A closer look to the system frequency 2005-12-01 /21/

At a normal switching operation in in a 400 kV station in the upper Lule älv (S1), disconnection of the shunt reactor, S-phase breaker pole does not open, which creates a dissymmetry, which causes the earth-fault protection to trip after about 300 ms. Simultaneously, the breaker failure protection for the faulty circuit-breaker is activated, and trips, after 170 ms, all objects connected to the same bus as the shunt reactor and sends a trip of generation signal to generation connected to the line to Norway and to generation connected at a downstream 400 kV station. When the 400 kV bus is tripped, the connection to Northern Norway is lost. The system loses about 2500 MW of generation and the frequency goes as low as 49.24 Hz. For 7 minutes and 20 seconds, the frequency is below 49.85. In Sweden, we lose about 800 MW generation When Northern Norway is separated from the rest of the Nordic system, it had a surplus generation of about 1700 MW, which caused a high frequency in Northern Norway. Due to the spinning active reserve in Southern Norway, the transfer to Sweden the southern connection to Norway increased temporarily to about 2800 MW. In S1, the operators tried to manually energize the tripped bus twice; both times the breaker tripped again by the earth-fault protection due to the dissymmetry in the reactor bay. The relay protection system and the generation curtailment system operated properly.

Other actions activated in relation to the disturbance:

- Gas turbines were started, both automatically and manually.
- Emergency power (EPC) was activated on 3 HVDC links.
- Reserves in Finland and Denmark were activated, as well as slow reserves in Sweden.
- Electrical heating of about 50 MW was disconnected
- Maintenance personnel was called to check the breaker in Porjus
- Northern Norway was re-synchronized at 15:26
- In S1 the faulty breaker was isolated and the bus was re-energized at 16:20.

No nuclear unit was affected by the disturbance.

A frequency recording by Svenska kraftnät from this event is shown in Figure 32.

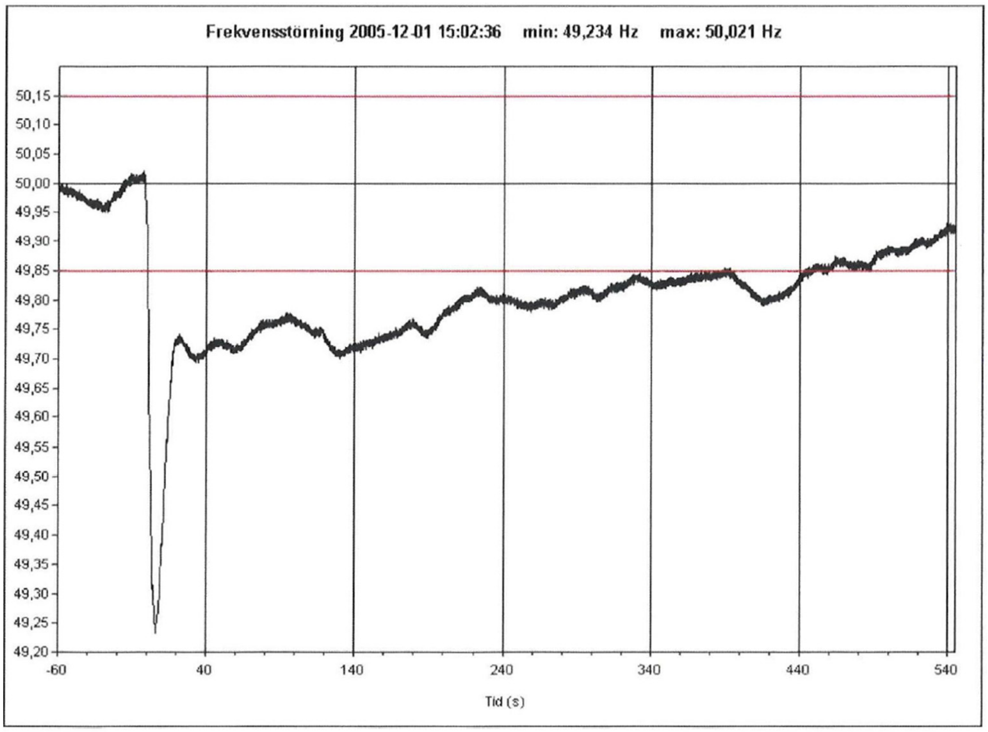


Figure 32 Frequency recording 2005-12-01 /22/

3.11.2 Conclusions and lessons learned

The disturbance shows how a rather simple shortcoming of the only non-redundant component in the fault clearing system, the circuit-breaker, might jeopardize the power system integrity. Although, the major transmission system substations now are refurbished, there are still some odd fault locations in combinations with "hidden failures"[3] in the fault clearing system, that might challenge the system integrity.

1. Breaker failure protection might cause a significant amount of breakers to trip, and should be carefully designed, especially for bus couplers and other sensitive breakers, in combination with large transmission capacity, large generation, or heavy load, affected by a backup fault clearance.
2. Breaker failures are rare, but they happen. It might be relevant to consider also doubling the number of breakers in sensitive designs.

3.12 LOSS OF OSKARSHAMN 3, 2011-11-04

The loss of Oskarshamn 3 at full power output in 2011 is believed to be one of the single point of failures with the deepest frequency decay, deeper than expected at the time of the test. Therefore, this disturbance is chosen for deeper investigation.

[3] "hidden failure" is a term often used when there is a failure in the protection system that is not shown until a fault clearance is called for.

3.12.1 Deeper investigation of the loss of Oskarshamn 3, 2011-11-04

The main part of this deeper investigation is based on material provided by Svenska kraftnät /22/.

The maximum frequency dip ever in the Nordic system, due to a single loss of generation, Oskarshamn 3 at about 1400 MW, 2011-11-04, down to 49.36, is presented in Figure 33. Three HVDC links provided emergency power of 200+50+150 MW. Six gas turbines in Southern Sweden were automatically started, and the frequency control increased the generation in Norway and in Northern Sweden. Regional network operators noticed load shedding START signals, but no trip. At the time for the Oskarshamn 3 trip, under excitation tests were running in the region and therefore the voltages were high before the trip. Thus, no low voltages were noted in relation to the disturbance.

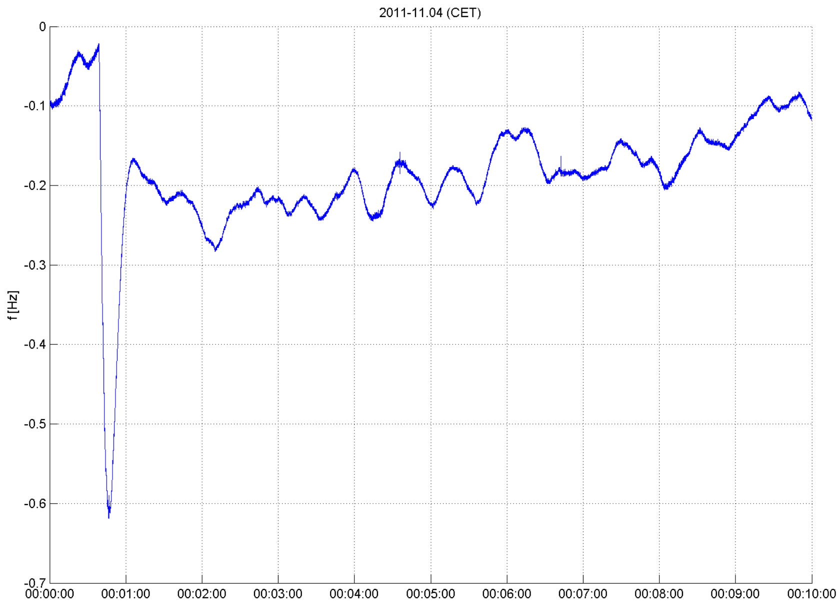


Figure 33 Frequency drop due to trip of Oskarshamn 3 at 1400 MW output /21/

3.12.2 Conclusions and lessons learned

As renewable generation is more and more introduced, the system inertia is reduced, and the remaining hydro power has to take care of the FCR-D. The surplus of spinning active power reserves, as experienced at the disturbance 2003 described in Section 3.4, will not remain and the system will be operated closer to its limits. Therefore, more attention needs to be paid to ensuring the system inertia, the speed and quality of the FCR-D contributions.

1. The frequency dip after a dimensioning loss of generation, might be deeper and faster than expected, due to uncertainties in inertia, FFR, and FCR-D.
2. The margins are smaller, with basically no control capacity surplus.

4 NPPs and big events in the Future Nordic Power Grid

This section summarizes the characteristics of the large disturbances described in Chapter 3, in a format applicable to the future Nordic power system. The aim is to identify potential support from the Nordic NPPs to preserve the power system integrity in stressed and unstable situations. The overall concept is to identify the steady state and dynamic operational ranges of the NPPs that are suitable for grid support in emergency situations and lie outside formal requirements (ENTSO-E RfG and national associated regulations), but within secure operational limits with respect to nuclear and assets.

At the end of this chapter, the next steps towards optimizing the interaction between grid and generation to extract maximum benefit for society are discussed.

4.1 THE FUTURE NORDIC GRID

For the remaining lifetime of the present Nordic NPPs, significant power system changes are expected. The change in generation mix, from large synchronous generators, connected at higher voltage levels, to converter connected generation, connected to all voltage levels throughout the system, has already started and will continue. The total wind power generation in Sweden is often larger than the nuclear generation and larger than the hydro generation. The power flows in the grid, especially in the transmission grid, will be and have already started to be much more diversified and volatile. This trend is not only caused by the altered generation mix but depends also on new connections to the Nordic system and may further be affected by shorter settlement periods.

The transmission system development plans in Sweden for the near future are documented by Svenska kraftnät in /23/ and for the Nordics by the Nordic TSOs in /24/.

The converter connected generation has so far not significantly contributed to the ancillary services needed for a reliably functioning power system. All kinds of frequency control, from inertia and fast frequency reserves to restoration reserves, for normal operational conditions as well as for disturbed situations, will be more pronounced in the future. More and more large HVDC connections are emerging in the Nordic transmission grid, both links to other systems and connection links to offshore generation. These links and connections appear more vulnerable and prone to trip for grid disturbances, than traditional synchronous generators. Quite a few links are located relatively close to each other, e. g. Baltic Cable, SwePol Link, NordBalt, and Hansa PowerBridge. Due to market conditions, it is very likely that these links are all fully loaded either towards or from the Nordic system. This results in a potential risk of a significant imbalance between generation and load in case of common mode disturbances.

Voltage control and reactive power support is required also from converter connected generation, but the contributions from the remaining NPPs will be even more critical.

With respect to power oscillation damping, all kinds of contributions will be welcome.

4.2 LARGE DISTURBANCE CHARACTERIZATION

The large disturbances described and analyzed in Chapter 3 can be categorized with respect to their origin and power system consequences into five main groups:

1) Voltage deviations: loss of transmission capacity
   - A reactive power issue.
     a. Hamra (1983) – The South Swedish part
     b. Salt storm in Southern Sweden (1999)
     c. Zeeland and Southern Sweden (2003)
     d. South Florida (1985)

2) Frequency deviations: loss of production or load or from system separation
   - An active power issue.
     a. Hamra (1983) – The North Sweden and Finland parts
     b. Underfrequency event London (2019)
     c. Separation of Continental Europe (2006)
     d. Loss of NordLink HVDC (2022)
     e. Loss of several units in Lule River (2005)
     f. Loss of Oskarshamn 3 (2011)

3) Oscillations: loss of transmission capacity
   - A control system issue.
     a. Stenkullen (1997)

4) Combinations of voltage and frequency deviations and oscillations
     a. North America Blackout (2003)

5) Non power system response related outages
   - Antagonistic direct breaker control or similar
     a. Ukraine Attack (2015)

The potential of NPPs to mitigate big events in the future Nordic power grid will be addressed per disturbance type in the following subsections.

4.2.1 Voltage deviations: loss of transmission capacity

So far, the transmission capacity limit through the critical bottle necks in Sweden (Snitt 2 and Snitt 4) have been set according to the risk of voltage instability, associated with the North-South power flow. The two disturbances Hamra 1983, described in Subsection 3.1, and Zeeland and Southern Sweden 2003, described in Subsection 3.4, also clearly illustrate the vulnerability of the system with respect to voltage instability.

In voltage instability situations, fast and sustainable reactive power support is of utmost importance for a controlled return to normal operational conditions. One problem is that the voltage issues might be local, and not observable remotely. Thus, emergency voltage support systems could be developed to temporarily increase the local voltage set-point at the NPPs in case of transmission system voltage problems.

Furthermore, it is of utmost importance that the NPPs stay grid connected, with maximum or limited reactive power output, when required by the grid conditions. For that purpose, proper coordination between the rotor current limiter, the stator current limiter, and the overexcitation related protections must be ensured.

4.2.2 Frequency deviations: loss of production or load or from system separation

Frequency control will be a more and more scarce resource. When renewable energy systems, in the form of intermittent wind and solar generation, increase in the generation mix, specifically upwards frequency regulation will be critical (power output increase, due to frequency decrease). Thus, providing FCR-N in both directions, during normal NPP operation, instead of maximum output, might be good business in the future /25/.

With respect to disturbances, the synchronous generators provide inertia to the system, which slows down the frequency decay at sudden generation deficit situations. Since the inertia contribution is there by nature, as long as the unit is synchronized, it may be difficult to classify inertia as an independent ancillary service in situations with enough inertia. However, in situation when the TSO purchases FFR, it seems reasonable with reimbursement of inertia provided.

At large frequency excursions, upwards as well as downwards, it is extremely important that the nuclear units stay grid connected as long as possible, with respect to the duration of the frequency deviation. It would also be valuable to the power system if NPPs could contribute to the frequency disturbance control (FCR-D upwards and downwards).

Furthermore, considering the size of the NPP units, the trip levels should be diversified to avoid simultaneous tripping of several units, e. g. at the limits of the formal requirements.

4.2.3 Oscillations: loss of transmission capacity

There are formal requirements on damping and PSS-capability. However, at certain locations and at certain power system operational conditions, additional damping might be beneficial and could be agreed upon with the connecting TSO.

Properly dimensioned and controlled braking resistors have been shown to be an efficient way of damping large and reasonably slow oscillations /26/. Braking resistors can also be used to improve the transient angle stability, and thus increase the power output, without violating the critical clearing time or fault ride through criteria. Such braking resistors might be highly efficient at the Swedish NPPs. However, it has to be kept in mind that every equipment added to the power system is a potential source of failure and might mal-operate or just cause a failure and a subsequent disturbance during normal operation.

4.2.4 Combinations of voltage and frequency deviations and oscillations

Although a large disturbance can often be characterized as a voltage event or a frequency related event at the beginning of the disturbance, most disturbances end up in a mixture of voltage, frequency and phase-angle related issues. Some disturbances, especially in large systems evolve during a longer time typically tens of minutes to hours, with interactive loss of transmission capacity and loss of generation (load). The North American blackout in 2003, described in Subsection 3.6, was a typical combination of cascading events and temporary system stabilizations, followed by new events. In this particular disturbance, the slow dynamics of thermal line sagging played a major role in the stepwise evolution of the disturbance.

4.2.5 Non power system response related outages

The Nordic power system has so far been spared from major sabotage and from cyber attacks. To protect the power system from such types of antagonistic attacks, completely different measures have to be taken, since statistics and probabilistic methods are not applicable. It is more a matter of shielding and prevention, than of curative methods and remedial actions.

There are different ways of manipulating a power system through the control system. Some of them require access to the operations, such as breaker switching, while others might focus on measurement manipulations, providing false data leading to wrong, manual or automatic, actions.

Passwords, firewalls, access clearance, etc., are fundamental and must be implemented and operators need specific training to work in a digitally secure way.

4.3 OPTIMIZED POWER SYSTEM RELIABILITY

The deregulation of the electricity market from the 1990's and onwards has been centrally controlled by applying a top-down requirement specification methodology. It originates from ENTSO-E, with a focus on Continental Europe, and should be implemented and further specified by the different TSOs. There are some concerns that the specification promotes simplification of the tasks of the TSOs at the cost of requirements specified to establish an overall optimized power system.

A selective, probabilistic approach concerning NPP power output and system resilience with respect to worst case backup clearance of rare power system faults, would enhance the entire performance of the power system and improve the cost/benefit relation. For example, the low-voltage-ride-through requirement in the ENTSO-E network code on the requirements for generators, RfG, is set with respect to specific clearing time values, irrespective of back-up clearance solutions. Such a requirement disqualifies a significant potential to enhance the overall power system performance with smart switchgear design, advanced protection and control solutions, and efficient remedial action schemes.

4.4 POWER SYSTEM NEEDS AND SUPPORT RESOURCES

In the subsections above, the need and potential for enhanced NPP support to the transmission system is described. The remaining question then becomes, to what extent can such additional or extended support actually be offered by NPPs? And how would such a contribution compare to the potential contribution from renewable generation?

As previously discussed, there is great potential for the NPPs to identify the available volumes of support, delimited by legal requirements on one side and security limits for the nuclear process and asset endurance on the other side. Any potential NPP contribution to the power system integrity has to be designed and optimized with respect to volume, duration, and shape. There are many limits, such as thermal, mechanical, electric field, the nuclear process, etc., to take into consideration. The importance of not compromising successful transfer to house load operation when a nuclear unit is disconnected from the grid has also to be emphasized.

The obvious areas of potential contributions are related to frequency and voltage control in the following way:

- Frequency control during normal operation, FCR-N
- Active power boosting during a frequency decay, FCR-D upwards
- Active power reduction during a frequency raise, FCR-D downwards
- Reactive power boosting during a voltage decay
- Reactive power absorption during a voltage rise

The Nordic NPPs already today make significant contributions to the voltage and reactive power control, while the area of frequency and active power control is less utilized. In addition to the potential contributions above, other important support capabilities, that may be more difficult to quantify and reimburse, are discussed below.

Inertia significantly supports the power system in slowing down the frequency decay at sudden generation deficit situations. NPPs greatly contribute to the inertia since they are connected to the grid via a highspeed synchronous generator with a heavy turbine. Any synchronous machine intrinsically contributes to the overall inertia as soon as the unit is synchronized to the grid, and automatically reacts to active power imbalances without any control systems.

For certain grid situations, the need for reactive power at the connection points of the NPPs is much higher than the need for active power. Thus, a runback of active power in order to use the stator thermal capacity to fully utilize the reactive power capability might be beneficial /27/.

The value of house-load operation was emphasized after the Hamra 1983 disturbance, described in Subsection 3.1. Successful transfer to house-load operation enables NPPs to re-synchronize to the grid within a few hours, instead of within a few days which would be the case after a full stop.

The NPPs are of course equipped with Power System Stabilizers, PSSs, often tuned to damp local modes. In the future, the need for damping of wide area oscillations with larger magnitudes might be more pronounced.

4.4.1 Renewable Generation Support Possibilities

Renewable intermittent generation based on solar and wind cannot store the primary energy. Therefore, different types of energy storages are discussed and applied to smoothen out the intermittent energy inflow and consequently make the power generation from these resources more controllable. With such a setup, renewable energy could also provide different types of ancillary services and disturbance support. How much converter connected generation can contribute with voltage control and reactive power capacity is a matter of converter dimensioning.

A converter can also be designed to provide "artificial inertia" if combined with a relatively small energy storage. Such an inertia contribution differs from that supplied by synchronous generators in that it is dependent on the converter control system for its functioning. On the other hand, it can be quite freely designed.

The effects of the increased amount of power electronics in the power system is further elaborated in the EU project report /28/.

5 Triggering Events and Root Causes of the Future

This chapter covers triggering events and root causes that are expected to become more pronounced in the future and relates them to the big events described in Chapter 3.

5.1 CLIMATE CHANGE LEADS TO EXTREME WEATHER CONDITIONS

Climate change will lead to more extreme weather conditions that could affect geographically close components simultaneously. Such a common trigger may lead to more than one simultaneous fault, which a power system based on the N-1 principle is not designed to withstand.

Historic events, such as the South Florida 1985 outage, described in Section 3.5, highlight the devastating consequences extreme weather conditions may results in for the power system.

To tackle the more frequent extreme weather-related issues, it may be that the power system may need to be designed to withstand N-2 conditions. That is already the case today in some parts of the Nordic power system but perhaps it needs to be implemented to a greater extent in the future.

Another idea would be to change to a more selective, probabilistic approach in designing the power system resilience, with smart switchgear design, advanced protection and control solutions, and efficient remedial action schemes. Changing from the deterministic N-1 principle may not be realistic or even desirable, but adding probabilistic action schemes at specific, vulnerable parts of the power system could be an option. A probabilistic risk assessment approach in the operational phase of the European transmission systems is under way. It emanates from the European Union Commission Regulation (EU) 2017/1485 of 2 August 2017 (System Operation Guide Line) Article 75. It is further outlined in ACER Decision on CSAM: Annex I "Methodology coordinating operational security limits", 19 June 2019.

There are other, more specific, changes in the design of the power system that would also reduce the risk of two or more fault with a common trigger. For example, parallel lines could be located some distance apart or double circuit transmission towers could be avoided. Alternatively, the system could be designed to cope with the loss of both circuits of a double circuit line.

5.2 ENERGY TRANSITION LEADS TO MORE RENEWABLES AND INCREASED ELECTRIFICATION

Renewable energy, specifically converter connected generation, introduces new types of control system in the power system. In recent decades, the share of converter connected generation in the generation mix has increased rapidly and is expected to continue to grow. It is therefore of utmost importance that the related controls are designed to maintain the power system resilience.

The underfrequency event in London 2019, described in Subsection 3.7, shows the consequences of control systems that are not set and operated in compliance with grid code requirements. The reason being the complexity and inexperience with the control systems of renewable generation.

It is clear that the performance of converter connected generation, specifically the response to power system transients, must be thoroughly tested and verified.

More renewables in the system generally leads to less inertia and therefore a less resilient power system. They also result in less short circuit power, which increases the geographical spread of fault related voltage drops. In other words, NPPs and all other power system components, will probably experience a higher exposure to faults in the future.

The energy transition in general leads to a higher utilization level of the power system as well as to a wider variety of power flow patterns and consequently increases the stress level thereof.

5.3 MORE GLOBAL POWER GRIDS LEADS TO MANY HVDC LINKS

More and more large HVDC connections are introduced, both links between power systems and connection links to offshore generation. Due to market conditions, it is very likely that links are all fully loaded either towards or from a power system. Moreover, it appears that the HVDC converter power electronics might be more vulnerable to grid transients, resulting in a risk for trip of more than one HVDC connection from the same triggering network disturbance. Consequently, there is a risk of a significant imbalance between generation and load in case of common cause disturbance, close to or even larger than the dimensioning loss of a single source of power infeed in a power system.

Although no severe disturbance has occurred in the Nordic power system due to a trip of an HVDC link, there is a substantial risk for future disturbances due to the increased number of HVDC links with higher failure rates than conventional generation of similar size. With the increasing number of HVDC links connecting the Continental Europe system to the Nordic one, there might also be an increased risk that severe regional disturbances in Continental Europe may affect more than one HVDC link to the Nordic synchronous area.

5.4 DIGITIZATION OF THE POWER GRID

Like all technical fields, power systems become more and more digitized. Digitalization provides great opportunities to collect and access large volumes of data, automize data analysis and alert operators, run simulations quickly, and facilitate the communication between people, between people and components and between components.

The benefits of digitization are also associated with new risks, such as the vulnerability to cyber attacks and new types of human error.

Cyber attacks represent a new area of sabotage and power system interference that need new methods to withstand. Today, much of the power system resilience is based on curative methods and remedial actions. Looking ahead, the IT security of power systems must be designed to shield and prevent in order to withstand cyber attacks. That probably entails further implementation of passwords, firewalls, access clearance, etc., in the control systems. It is important to complement such system changes with specific user trainings to implement a digitally secure way of working.

There are different ways of manipulating a power system through the control system. The Ukraine cyber attack in 2015, described in Subsection 3.9, is an example of a cyber attack based on direct access to the operations. Another type of cyber sabotage might focus on measurement manipulations, providing false data leading to wrong, manual or automatic, actions. The most well-known attack of this type is probably the one directed to a nuclear-enrichment plant in Iran infected by the Stuxnet virus /29/.

Up to now, there are limited examples of cyber attacks on power systems but as digitization increases so does the risk of future attacks. In the near future, the digital systems may very well be the weakest link of power systems in terms of resilience. Therefore, cyber security must be prioritized and lessons must be learnt from other fields and society infrastructures.

More severe antagonistic threats like EMP (Electro Magnetic Pulse) may have the potential to destroy digitized components and systems over large areas /30/.

The increase of automized processes and decisions has many benefits but at the same time, operators become less experienced in manually operating the system, including mitigating disturbances. The lack of experience together with the incalculable amount of data available may lead to new types of human errors. To mitigate such risks, knowledge transfer between senior and junior operators must be ensured as well as extensive training on the digital tools used.

6 Conclusions

It is clear that several different factors contribute to increasing the stress on the power system and pushing it closer to its resilience limit:

- Climate change will lead to more frequent extreme weather conditions that can trigger multiple faults that traditional power systems are not designed to withstand.
- The increase of converter connected generation and HVDC links may introduce new types of disturbances.
- The digitization of power systems makes them vulnerable to cyber-attacks.

At the same time, the change in generation mix, from large synchronous generators, connected at higher voltage levels, to converter connected intermittent generation, connected to all voltage levels throughout the system, leads to less inertia and less short-circuit power in the system and less plannable power flows.

The trend is that the power system will be more and more stressed while being less and less resilient. Therefore, the need for ancillary services and disturbance support is of highest priority from a power system perspective.

NPPs are large, synchronous units with a primary energy source that is plannable. In the Nordics, there is potential for the NPPs to support the power system in stressed and unstable situations to a greater extent than simply complying with formal requirements. The next step would be to identify the steady state and dynamic operational ranges of the NPPs that are suitable for grid support in emergency situations and lie outside the formal requirements (ENTSO-E RfG and national associated regulations), but within secure operational limits with respect to nuclear and assets. From the Swedish NPPs it is emphasized that the support already today goes far beyond the formal requirements.

Specific examples of potential contributions could be:

- emergency voltage support systems could be developed to temporarily increase the local voltage setpoint at the NPPs in case of transmission system voltage problems
- emergency voltage support systems could be developed to temporarily increase the local voltage setpoint at the NPPs in case of a transmission system voltage problem, when longer term low voltages appear in the system and the NPP has additional reactive power resources to supply
- providing FCR-N in both directions during normal NPP operation, instead of maximum output, might be good business in the future when frequency control is expected to become increasingly scarce
- being reimbursed for providing inertia, at least in situations when the TSO purchases FFR
- providing FCR-D in both directions and staying grid connected as long as possible, with respect to nuclear and asset safety, at large frequency excursions
- diversify trip levels of NPPs to avoid simultaneous tripping of several large units

- Install properly dimensioned and controlled braking resistors to efficiently damp large and reasonably slow oscillations
- Implement smart switchgear design, advanced protection and control solutions, and efficient remedial action schemes on a selective and probabilistic basis

Any potential contribution of NPPs to the power system, as listed above, must be designed and optimized with respect to volumes, duration, and shape. There are many limits, such as thermal, mechanical, electric field, the nuclear process, etc., to take into consideration.

In the future, there will be more market-based solutions for ancillary services in the Nordics. That means it could be good business for the NPPs to contribute in addition to further strengthening their raison d'être.

Similar conclusions are valid for other plannable generation with similar unit size and stored energy. That would also include renewable intermittent generation in combination with different types of energy storages could also provide different types of ancillary services and disturbance support. The size of the contribution from converter connected generation is a matter of converter dimensioning. Such a setup could for example provide "artificial inertia", that depends on the converter control system for its functioning but can be freely designed.

It is obvious that the Nordic power system will need further support to handle disturbances in the future. There is a large untapped potential for the NPPs to explore and contribute more than they already do today. The greatest benefits of NPPs, compared to other power generating units, are:

- NPPs are large units connected at high voltage levels – easily controlled
- NPPs are synchronous units – automatically provide inertia
- The power output of NPPs is plannable – primary energy source storable
- The Nordic NPPs are located near high load centers – no congestion issues

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CHARACTERIZATION OF BIG EVENTS SUCH AS TRIPS OF BIG POWER PRODUCING UNITS OR HVDC LINKS

This report describes and characterizes large disturbances, and investigates the importance of the remaining nuclear power units in the Nordic power system, in the light of the ongoing energy transition towards intermittent converter connected generation.

A set of historical events are described and analyzed, and specific attention is paid to triggering events and root causes that are likely to become more significant in the future Nordic system. Other events provide insights into likely courses of events for the Nordic power system. A third category is relevant for the effect on and potential of Nuclear Power Plants (NPPs) during big events.