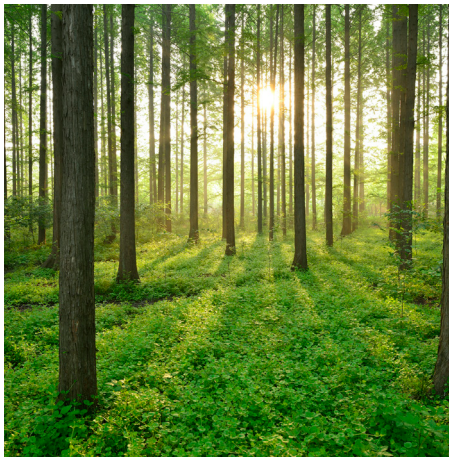


TRENDS OF FREQUENCY DEVIATIONS

RAPPORT 2025:1091



GRID INTERACTION WITH
NUCLEAR POWER PLANT
OPERATIONS, GINO



Trends of frequency deviations –
Frequency quality in the Nordic Power system during the last two
decades and its correlation with nuclear plants' inertia and wear and tear

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Foreword

This report forms the results of a project performed within the Energiforsk Energiforsk Grid Interaction with Nuclear power plant Operations (GINO) Program

The GINO Program aims to increase the knowledge of aspects of the interactions between the external grid and the Nordic nuclear power plants. Part of this is to investigate technical issues.

Frequency deviations in the Nordic Power System have been a growing concern over the past two decades, impacting overall grid stability and performance.

For nuclear power plants, maintaining stable frequency is crucial to ensure operational safety and longevity of critical components.

This study examines historical trends in frequency deviations, their impact on nuclear plant operations, and the effectiveness of current and future mitigation strategies.

The findings indicate improved frequency quality in recent years, with recommendations for further enhancements to support nuclear plant reliability and grid stability.

The study was carried out by Viktorija Dudjak, Jonas Persson, and Markus Björklund, Vattenfall Research & Development. The study was performed within the Energiforsk GINO Program, which is financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft, Karlstads Energi, the Swedish Radiation Safety Authority and Svenska Kraftnät.

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

Summary

This project has investigated a number of concerns about quality of the grid frequency in the Nordics and its impact on nuclear power plants in Finland and Sweden. The report is focused mainly on the following topics:

- Historical trends of frequency deviations in the Nordic Power System during the years 2003 – 2023 and future trends that can be seen today.
- Investigation of how system inertia varies with nuclear and other power production over time, as well as different system services in frequency control (primary and secondary control) of the Nordic Power System mostly during the years 2016 – 2023.
- Frequency deviations impact on life expectancy of components in nuclear power plants.
- Analysis of current and future trends in frequency quality and system services in the Nordic Power System.

The work has been performed by *i)* interviews with specialists from the nuclear power plants in Finland and Sweden, *ii)* interviews with specialists from the TSOs (SvK and Fingrid), *iii)* analysis of statistics, and *iv)* literature studies.

The frequency quality has been investigated in this report for the last two decades (2003 – 2023). The KPI¹ – *minutes outside of frequency range ± 0.1 Hz* has during 2005 – 2011 increased to high values which was caused by HVDC-links that were allowed to do large changes in transmitted power and direction. In the second decade these HVDC-links have had regulations on how large the changes could be which led to an improved frequency quality.

Frequency quality has improved over the course of the last four years when we observe average daily frequency in period between 2003 and 2023. The average daily frequency remains within limits of ± 0.1 Hz through all the years and there is also a trend of average value being closer to 50.0 Hz that can be observed in the last four years. This, together with increased frequency quality in terms of KPI – *minutes outside of frequency range ± 0.1 Hz*, implies the trend that frequency quality has improved in the Nordic Power System during the last four years (2020 – 2023).

The improvement in the KPI during recent years can be a result of the introduction of Automatic Frequency Restoration Reserve (a-FRR) in the year 2013. The volumes of a-FRR has since then increased which can be one reason behind the improvement of the KPI during the last years.

There are however rather long periods of over-frequency which are consequences of erroneous forecasts in power production, lot of wind power production, low loads, and a lack of down-regulating power as a-FRR down and m-FRR down.

¹ KPI means Key Performance Indicator

Statistically it is shown in the report that the frequency is more often outside the interval ± 0.1 Hz around the hour shift, i.e., around the full hour. This is a consequence of how energy is traded in the Nordic Power System.

There are very rare events when frequency exceeds 50.3 Hz. These high peaks in frequency is a fairly new phenomenon in the Nordic Power System. It will remain a part of the future system due to the large HVDC-links that have been built in the recent years between the Nordic Power System and close-located other synchronous systems.

No connection between low levels of inertia and low frequency quality (in the sense of the KPI – *minutes outside of frequency range ± 0.1 Hz*) can be found in the studied material. On the contrary, we observe that during summer months, when inertia is often very low in the system, frequency quality is better than during other months of the year. In spite of this it is important to understand that inertia is an important system quantity in case of larger transient events like for instance sudden disconnections of large production units when system inertia supports the power system so that the frequency deviation becomes smaller. During periods of low amounts of system inertia, the Nordic TSOs are compensating this by buying Fast Frequency Reserve (FFR) since year 2020 which responds very quickly to steep frequency changes and compensates for the lost power in the grid.

Although the annual peak levels of inertia coming from nuclear power plants decreased during the period (2016 – 2023), in year 2024 the annual peak of inertia from nuclear power plants is back to almost the same level as before decommissioning of Oskarshamn 1, Ringhals 1, and Ringhals 2 starting in 2016 as a result of the commission of Olkiluoto 3 during year 2023.

The amount of inertia from nuclear power plants seems not to decrease further in the coming decades since at the moment several of the nuclear owners in the Nordic countries are examining lifetime extensions of the existing plants. In addition, there are discussions of building new NPPs in Sweden in the coming decades which will further add inertia from nuclear power plants.

Because of large HVDC-links that have recently been connected to the Nordic Power System and that several times every year are shut down, high frequency values have appeared during the last four years. Also several occurring disconnections of nuclear power plants have resulted in even larger frequency dips during the last four years. If the trend of that these dips in frequency becomes larger and larger and is caused by decreasing system inertia, is hard to state. In order to do so, each event must be analyzed and for instance investigate the actual amount of inertia in the Nordic Power System for each frequency dip as well as other characteristics at that very moment.

In general, the NPP operators do not report any experience with wear and tear caused by grid frequency deviations. More concern is raised from the NPP operators around grid voltage disturbances impact on wear and tear of equipment, which might be of interest for future work.

We cannot see any connection between high amounts of wind power and low frequency quality since during the months of high wind power production the grid frequency shows a better frequency quality.

The Nordic TSOs prepare for the future worst-case scenario which is small amount of inertia in the system and continue therefore to develop the product FFR since it has shown to be a good tool to compensate for periods of low levels of inertia.

The Nordic TSOs want to see larger volumes of regulating power, a-FRR and m-FRR, which are sometimes lacking in the control of the power system, leading to long durations of over- or under-frequencies.

Acknowledgement

We would like to thank Henrik Ekestam, Svenska Kraftnät, Anders Lundberg Fingrid, Anders Angantyr FKA, Magnus Adolfsson FKA, Sofia Johansson RAB, Magnus Knutsson RAB, Sandra Ekman RAB, Jonas Olandersson RAB, Seppo Härmälä TVO, Ari Kanerva Fortum, Timo Rautio Fortum, Jonas Jönsson OKG, Daniel Johansson OKG, Robert Wallmark OKG, and Håkan Svahn Uniper and OKG for sharing valuable information during the interviews.

We would also like to thank Linn Saarinen from Svenska Kraftnät for providing us with frequency data from 2003 until 2014.

Keywords

Frequency, frequency quality, equipment wear and tear, nuclear power plants, NPPs, Transmission System Operators, TSOs, HVDC-links, primary and secondary control, system services.

Sammanfattning

Detta projekt har undersökt ett antal frågeställningar kring frekvenskvaliteten i Norden och dess påverkan på kärnkraftverken i Finland och Sverige. Rapporten fokuserar huvudsakligen på följande ämnen:

- Historiska trender för frekvensavvikelser i det nordiska elnätet under åren 2003–2023 samt trender som kan förutses i framtiden.
- Undersökning av hur nätets tröghet varierar med kärnkraft- och övrig produktion över tid samt olika systemtjänster för frekvenskontroll (primär- och sekundärreglering) av det nordiska elsystemet under åren 2016–2023.
- Frekvensavvikelsernas påverkan på livslängden för komponenter i kärnkraftverk.
- Analys av nuvarande och framtida trender i frekvenskvalitet och systemtjänster i det nordiska elsystemet.

Arbetet har utförts genom *i)* intervjuer med specialister från kärnkraftverken i Finland och Sverige, *ii)* intervjuer med specialister från systemoperatörerna (SvK och Fingrid), *iii)* analys av statistik och *iv)* litteraturstudier.

Frekvenskvaliteten har undersökts i denna rapport för de senaste två decennierna (2003–2023). KPI² – *minuter utanför frekvensintervallet $\pm 0,1$ Hz* ökade under perioden 2005–2011 till höga värden, vilket orsakades av HVDC-länkar som var tillåtna att göra stora förändringar i överförd effekt och riktning. Under det senare decenniet reglerades dessa HVDC-länkar kring hur stora förändringarna kunde vara, vilket ledde till en bättre frekvenskvalitet.

Frekvenskvaliteten har förbättrats de senaste fyra åren när man ser på genomsnittlig daglig frekvens under perioden 2003–2023. Den genomsnittliga dagliga frekvensen hålls inom gränserna för $\pm 0,1$ Hz genom alla år, och det går också att observera en trend där det genomsnittliga värdet är närmare 50,0 Hz under de senaste 4 åren. Detta, tillsammans med förbättrad frekvenskvalitet när det gäller KPI – *minuter utanför frekvensintervallet $\pm 0,1$ Hz*, tyder på att frekvenskvaliteten har förbättrats i det nordiska elsystemet under de senaste fyra åren (2020–2023).

Förbättringen i detta KPI kan vara ett resultat av introduktionen av Automatic Frequency Restoration Reserve (a-FRR) fr.o.m. år 2013. Volymerna av a-FRR har allt sedan dess ökat vilket kan vara en anledning till ett förbättrat KPI under de senaste åren.

Det finns långa perioder av överfrekvens vilka är konsekvenser av felaktiga prognoser, mycket vindkraftsproduktion, låg belastning samt brist på nedreglerande effekt, dvs. brist på a-FRR down och m-FRR down.

² KPI betyder Key Performance Indicator, kvalitetsindex

Statistiskt sett visar det sig att frekvensen mer ofta ligger utanför intervallet $\pm 0,1$ Hz vid timskarvarna (vid hel timme) jämfört med under övriga timmen vilket är en konsekvens av hur effekt handlas i Norden.

Det är mycket sällsynt att frekvensen överstiger 50,3 Hz. De höga topparna i frekvens är ett relativt nytt fenomen i det nordiska elsystemet. Det kommer att förbli en del av det framtida systemet på grund av de stora HVDC-länkar som byggts de senaste åren mellan Norden och intilliggande andra synkrona system.

Ingen koppling mellan låga nivåer av tröghet och låg frekvenskvalitet (i bemärkelsen KPI – *minuter utanför frekvensintervallet $\pm 0,1$ Hz*) kan påvisas i det studerade materialet. Tvärtom observerar vi att under sommarmånaderna, när trögheten ofta är mycket låg i systemet, är frekvenskvaliteten bättre än under de andra månaderna på året. Dock är det viktigt att förstå i detta sammanhang att trögheten är viktig att ha tillgång till vid större transienta förlopp som t.ex. plötsliga stora produktionsbortkopplingar för att undvika stora frekvensavvikelser. Om trögheten då är låg kompenserar de nordiska TSOerna sedan år 2020 detta genom att köpa in Fast Frequency Reserve (FFR) vilket de nordiska stamnätsoperatörerna (TSOerna) framgångsrikt har etablerat som en produkt för att användas under perioder med brist på tröghet. FFR svarar mycket snabbt på kraftiga frekvensändringar och kompenserar för förlorad produktion i nätet.

Trots att de årliga toppnivåerna för tröghet från kärnkraftverk minskade under perioden (2016–2023), är den årliga toppen för kärnkraftens tröghet nu (år 2025) tillbaka till nästan samma nivå som före nedläggningarna började 2016 av Oskarshamn 1, Ringhals 1 och Ringhals 2 vilket är en följd av idrifttagningen av Olkiluoto 3 under år 2023.

Mängden tröghet från kärnkraft kommer inte att minska ytterligare under de kommande decennierna, eftersom flera av kärnkraftsägarna i Norden för närvarande undersöker ytterligare livstidsförlängningar av de befintliga verken. Dessutom finns det idag (2025) diskussioner kring att bygga ny kärnkraft i Sverige under de kommande decennierna.

På grund av stora HVDC-länkar som nyligen kopplats in till det nordiska systemet och som med jämna mellanrum abrupt stängs ned har högre och oftare förekommande höga frekvensavvikelser förekommit under de senaste fyra åren. Även flera förekommande plötsliga bortfall av kärnkraftsproduktion har bidragit till att djupa frekvensavvikelser har förekommit under de senaste fyra åren. Om de senare avvikelserna är orsakade av lägre tröghet i det nordiska systemet är svårt att avgöra. För att avgöra det behöver varje händelse analyseras vilket inte har gjorts i detta arbete.

Generellt sett rapporterar inte kärnkraftverksoperatörerna om någon erfarenhet av slitage orsakad av frekvensavvikelser i nätet. Mer oro uttrycks istället från operatörerna kring påverkan från spänningsstörningar på slitage av utrustning, vilket kan vara av intresse för framtida arbete.

Ingen koppling går att se mellan stora mängder vindkraft och låg frekvenskvalité, eftersom frekvenskvaliteten är bättre under de månader som innehar hög vindkraftsproduktion.

De nordiska TSOerna förbereder sig för alla scenarier, vilket inkluderar små mängder tröghet i systemet, och fortsätter därför att utveckla FFR-produkten eftersom den har visat sig vara ett bra verktyg för att kompensera för låga nivåer av tröghet.

De nordiska TSOerna vill se större volymer av reglerkraft, a-FRR och m-FRR, vilka ibland saknas i styrningen av elsystemet, vilket leder till långa perioder med över- eller underfrekvenser.

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1 Historical and future trends of frequency deviations in the Nordic Power System

The Synchronous Nordic Power System consists of Norway, Sweden, Finland, and Eastern Denmark (DK2). These four countries and parts of countries are synchronously connected and have therefore a common synchronous grid frequency. The Nordic Power System is also connected through High-Voltage Direct Current-links (HVDC-links) to the other synchronous areas; Continental Europe, Great Britain, and the Baltic Countries (which is synchronized to Continental Europe since February 9, 2025), see Figure 26.

The Back-to-Back-connection between Finland and Russia is out of operation since May 14, 2022.

The quality of the frequency in the Nordic Power System is maintained by system quantities such as;

- System inertia,
- Primary Frequency control which consists of Frequency Containment Reserve-Normal (FCR-N) and Frequency Containment Reserve-Disturbed (FCR-D),
- Secondary Frequency control which consists of Automatic Frequency Restoration Reserve (a-FRR) and Manual Frequency Restoration Reserve (m-FRR),
- Emergency Power Control (EPC), delivered by HVDC-links that can, depending on their actual status, quickly start to import power to the Nordic Power System in case of a sudden lack of power in the system.
- Fast Frequency Reserve (FFR); today (2025) this is mainly delivered by batteries,
- Inherent capacities such as the system loads' dependence on voltage and frequency,
- System's ability to withstand for N-1 events. In the Nordic Power System the larger events include disconnection of large power plants such as nuclear as well as disconnection of HVDC-links (listed as N-1 events).
- Gas turbine disturbance-reserve in Sweden is automatically started at significant underfrequency events

The quality of the frequency is studied in this work, and it has been discussed how frequency quality should be measured and explained. It would be possible to analyze different grid events which result in large frequency deviations. However, for each of these events it is rather difficult to understand how parameters of the system such as the size of the disturbance, inertia, primary control, secondary control, Emergency Power Control, load's dependence on voltage and frequency, etc. are influencing the system and to understand why the frequency is as it is

during these events. In this work large events are discussed but mostly frequency quality is discussed related to how often it is outside of nominal by ± 0.1 Hz.

Frequency quality is commonly defined as the operating time inside a predetermined standard band of frequency. In the Nordic Power System the requirement is defined as **minutes outside of the standard frequency** range, of 49.9 – 50.1 Hz and, in the following section, this is the main metric used to evaluate *frequency quality*.

The goal of this study is to analyze frequency data in Nordic Power System from the last two decades and give indication on the overall trend of frequency quality in the system. What is the trend of frequency quality? Is it degrading or improving? Are there any significant changes in trend?

1.1 DATA SOURCING AND VERIFICATION

Open data on the electricity market and the power system [1] gives access to frequency data logged starting from 2015 with sampling time of 0.1 seconds. Therefore, additional data sources were needed in order to study trends in the last two decades.

Svenska Kraftnät gave access to frequency data logged starting for the time period between 2003 and 2014 (with sampling time of 5 seconds). All data used in this report was converted to EET/Helsinki Time Zone.

Since data logged between 2003 and 2014 were only available with sampling time of 5 seconds, higher frequency data between 2015 and 2023 needed to be downsampled to 5 seconds.

Downsampling always means a loss of information, therefore next step is to verify how this loss of information affects **observing trend** of frequency quality, *minutes outside of frequency range*. In order to do that, frequency data in between 2017 and 2022 was resampled from 0.1 seconds to 5 seconds by average method, i.e. each 5 second data sample is calculated as average of 0.1 second samples. KPI *minutes outside of frequency range ± 0.1 Hz* was calculated and compared with the same KPI published in Fingrid report [2] and in [3]. In the Nordic Power System, it is defined that the maximum number of minutes outside the standard frequency range (± 0.1 Hz) is 15 000 minutes per year [3].

Figure 1 shows that, with acceptable level of information loss, we can still capture the trend of the KPI for different frequency ranges observed. Therefore, we continue using frequency data with 5 seconds sampling time throughout the document when calculating KPI.

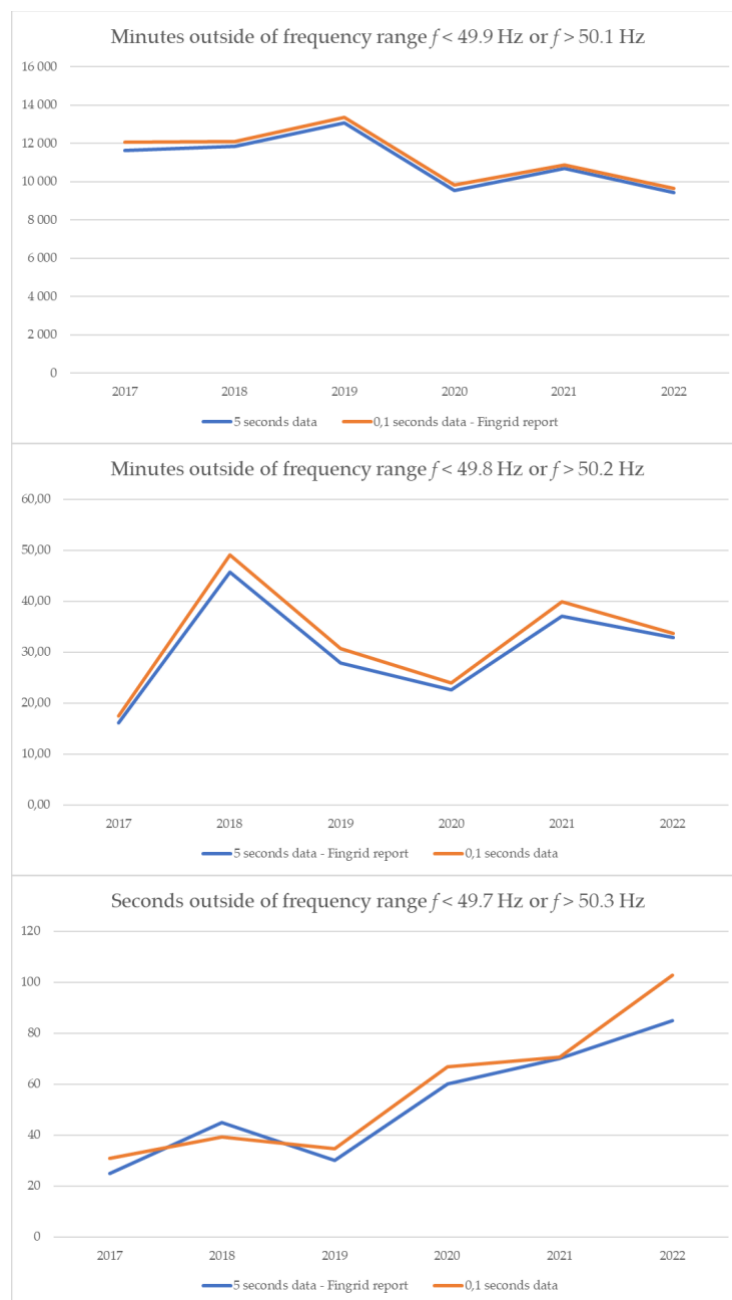


Figure 1: Comparison of KPI minutes/seconds outside of frequency range calculated with 5 seconds data (blue) and 0.1 seconds data (orange)

1.2 FREQUENCY QUALITY ANALYSIS FOR THE PERIOD BETWEEN 2003 AND 2023

We proceed to analyze the frequency quality by using 5 seconds data. Table 1 presents the results, showing KPI minutes outside of frequency range, together with Figure 2.

A significant trend of worsening of the KPI is seen since the middle of first decade in 21st century (2005 – 2011), with stagnation in the second decade (2012 – 2019), and with slight trend of improving in the last 4 years (since 2020) in Figure 2. The stagnation between (2012 – 2019) happens except for the years 2016 and 2019 which is analyzed later in Figure 5.

In that matter, we observe what changes happened in the Nordic energy mix in the same period, and if it is possible to make conclusions. Trend of larger penetration of renewables (mostly wind energy), as referenced later in section 4, is observed in the last two decades, but with significant increase after 2010. It is therefore not possible to give any correlation between frequency quality and changes in energy generation mix in the Nordic Power System just by observing these two variables.

Between 2005 – 2011 the numbers of HVDC interconnectors were increasing, and their operation were not as efficiently operated as today, which led to large abrupt change of power and worsened frequency quality during these years. Later, the TSOs introduced new rules on how to operate HVDC interconnectors, which improved the frequency quality. More details are given in section 4.

The improvement in the KPI shown in Figure 2 during recent years can be a result of the introduction of Automatic Frequency Restoration Reserve (a-FRR) in the year 2013. The volumes of a-FRR has since then increased which can be one reason behind the improvement of the KPI – *minutes outside of frequency range ± 0.1 Hz* during the last years.

Table 1: Minutes outside of frequency range $f > 50.1$ Hz or $f < 49.9$ Hz between 2003 and 2023

YEAR	DATA AVAILABILITY [%]	$f > 50.1$ Hz (MIN)	$f < 49.9$ Hz (MIN)	TOTAL (MIN)
2003	98.101	3 168	3 073	6 242
2004	99.998	2 729	2 470	5 199
2005	99.726	2 425	1 823	4 248
2006	99.726	2 908	2 169	5 077
2007	99.713	3 052	2 446	5 498
2008	99.935	3 796	3 335	7 130
2009	99.262	4 921	4 194	9 115
2010	99.724	6 136	5 036	11 172
2011	99.725	7 040	5 685	12 725
2012	99.841	6 624	5 013	11 636
2013	98.642	6 161	5 134	11 295
2014	99.541	5 358	4 966	10 324
2015	99.727	5 770	5 103	10 874
2016	99.459	7 462	6 472	13 934
2017	97.428	5 941	5 703	11 644
2018	98.735	6 190	5 646	11 836
2019	98.318	6 822	6 232	13 054
2020	98.409	5 200	4 343	9 543
2021	99.727	6 156	4 549	10 705
2022	99.541	5 246	4 182	9 428
2023	99.648	5 312	4 488	9 800
TOTAL	-	108 407	92 062	200 479

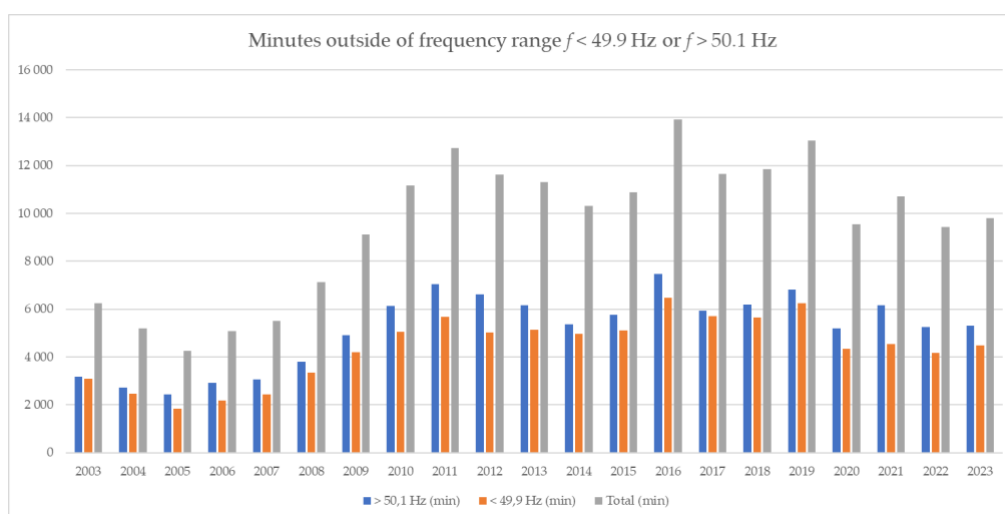


Figure 2: Minutes outside of frequency range $f > 50.1$ Hz or $f < 49.9$ Hz between 2003 and 2023

Further, we observe trends in KPI *minutes outside of frequency range* for two additional wider frequency ranges; outside of range $f > 50.2$ Hz or $f < 49.8$ Hz and outside of range $f > 50.3$ Hz or $f < 49.7$ Hz as shown in Table 2, Table 3, Figure 3, and Figure 4. While the value of KPI above 50.2 Hz in Table 3 and Figure 3 are higher through most of the years in the observed period, there are very rare events when frequency exceeds 50.3 Hz as shown in Figure 4 where this KPI, presented in blue color, is almost non-existent. In general, the value of KPI for frequencies for both ± 0.2 Hz and ± 0.3 Hz are constantly low through all the years.

In Table 3 we can see that the frequency has been higher than 50.3 Hz only for about 2 minutes and 40 seconds during the last 21 years and below 49.7 Hz for about 38 minutes during the last 21 years.

Table 2: Minutes outside of frequency range $f > 50.2$ Hz or $f < 49.8$ Hz between 2003 and 2023

YEAR	$f > 50.2$ Hz (MIN)	$f < 49.8$ Hz (MIN)	TOTAL (MIN)
2003	0.50	5.42	5.92
2004	0.50	7.58	8.08
2005	1.08	6.83	7.92
2006	0.75	4.58	5.33
2007	5.75	7.33	13.08
2008	5.75	5.17	10.92
2009	9.67	9.67	19.33
2010	9.67	19.83	29.50
2011	20.92	14.08	35.00
2012	20.25	5.83	26.08
2013	8.83	17.92	26.75
2014	14.08	14.83	28.92
2015	12.67	11.25	23.92
2016	15.67	17.67	33.33
2017	9.17	6.92	16.08
2018	28.33	17.42	45.75
2019	21.17	6.67	27.83
2020	5.83	16.75	22.58
2021	27.58	9.42	37.00
2022	18.33	14.50	32.83
2023	21.50	14.42	35.92
TOTAL	258.00	234.08	492.08

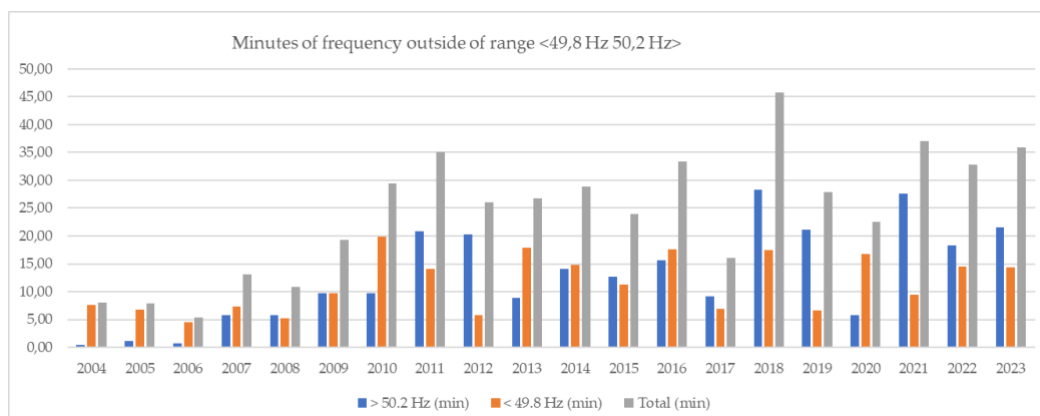


Figure 3: Minutes outside of frequency range $f > 50.2$ Hz or $f < 49.8$ Hz in period between 2003 and 2023

Table 3: Minutes/seconds outside of frequency range $f > 50.3$ Hz or $f < 49.7$ Hz between 2003 and 2023

YEAR	$f > 50.3$ Hz (MIN / S)	$f < 49.7$ Hz (MIN / S)	TOTAL (MIN / S)
2003	0.25 / 15	0.92 / 55	1.17 / 70
2004	0.08 / 5	2.67 / 160	2.75 / 165
2005	0.08 / 5	1.08 / 65	1.17 / 70
2006	0.00 / 0	1.08 / 65	1.08 / 65
2007	0.00 / 0	4.25 / 255	4.25 / 255
2008	0.08 / 5	0.92 / 55	1.00 / 60
2009	0.00 / 0	2.25 / 135	2.25 / 135
2010	0.00 / 0	12.67 / 760	12.67 / 760
2011	0.17 / 10	1.33 / 80	1.50 / 90
2012	0.00 / 0	0.83 / 50	0.83 / 50
2013	0.08 / 5	2.08 / 125	2.17 / 130
2014	0.08 / 5	0.50 / 30	0.58 / 35
2015	0.00 / 0	1.08 / 65	1.08 / 65
2016	0.33 / 20	0.92 / 55	1.25 / 75
2017	0.17 / 10	0.25 / 15	0.42 / 25
2018	0.08 / 5	0.67 / 40	0.75 / 45
2019	0.08 / 5	0.42 / 25	0.50 / 30
2020	0.25 / 15	0.75 / 45	1.00 / 60
2021	0.00 / 0	1.17 / 70	1.17 / 70
2022	0.50 / 30	0.92 / 55	1.42 / 85
2023	0.42 / 25	1.17 / 70	1.58 / 95
TOTAL	2.67 / 160	37.92 / 2 275	40.58 / 2 435

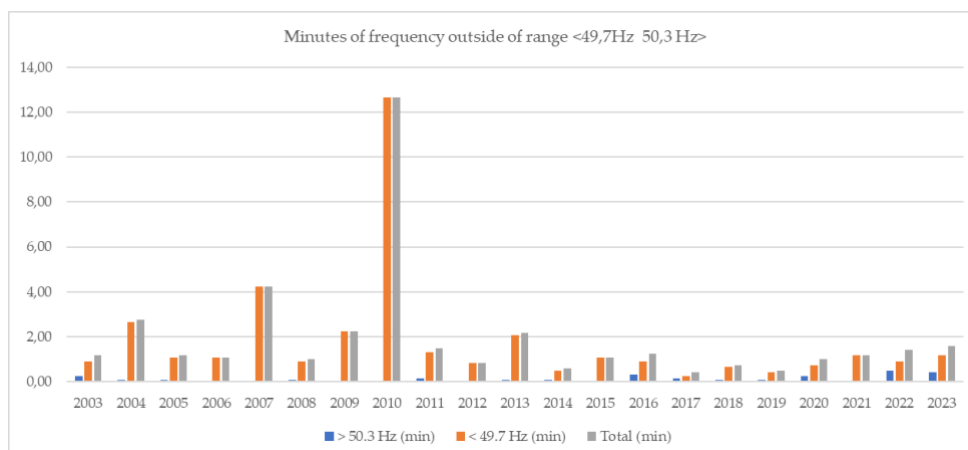


Figure 4: Minutes outside of frequency range $f > 50.3$ Hz or $f < 49.7$ Hz in period between 2003 and 2023

In Figure 2 we could see that the years 2016 and 2019 have the highest KPI – *minutes outside of frequency range ± 0.1 Hz*. Figure 2 shows how the KPI has developed during the years 2016 – 2019 month by month. From that we can see that year 2016 (in blue) had a spring with much higher monthly values of minutes outside of ± 0.1 Hz (January, February, March, April, and May). Also for year 2019 (in yellow) some months have much higher amount of minutes outside of ± 0.1 Hz (February, March, April, June, and December). A reason for this can be a lack of regulating resources such as a-FRR during parts of these two years.

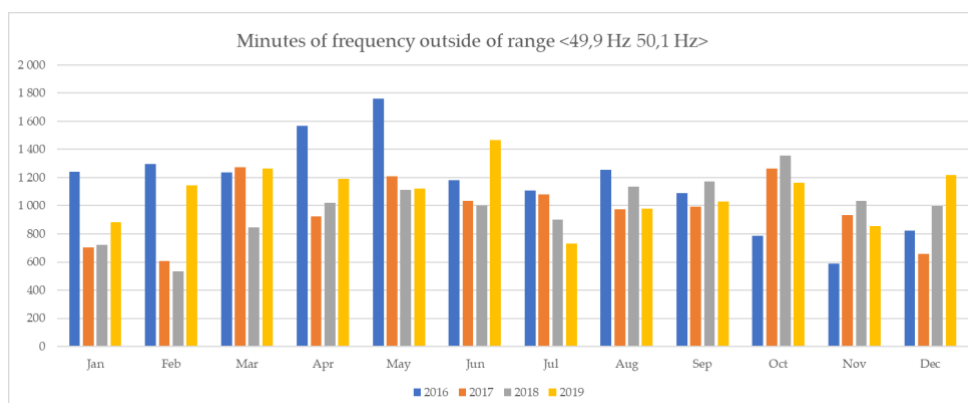


Figure 5: Monthly minutes outside of frequency range $f > 50.1$ Hz or $f < 49.9$ Hz in period between 2016 and 2019

In Figure 6 we observe average daily frequency in the period between 2003 and 2023. While average daily frequency remains within limits of ± 0.1 Hz through all the years, a trend of average value being closer to 50 Hz can be observed in the last four years. This, together with increased frequency quality in terms of *KPI minutes outside of frequency range*, implies the trend that frequency quality has improved in the Nordic Power System in the last four years.

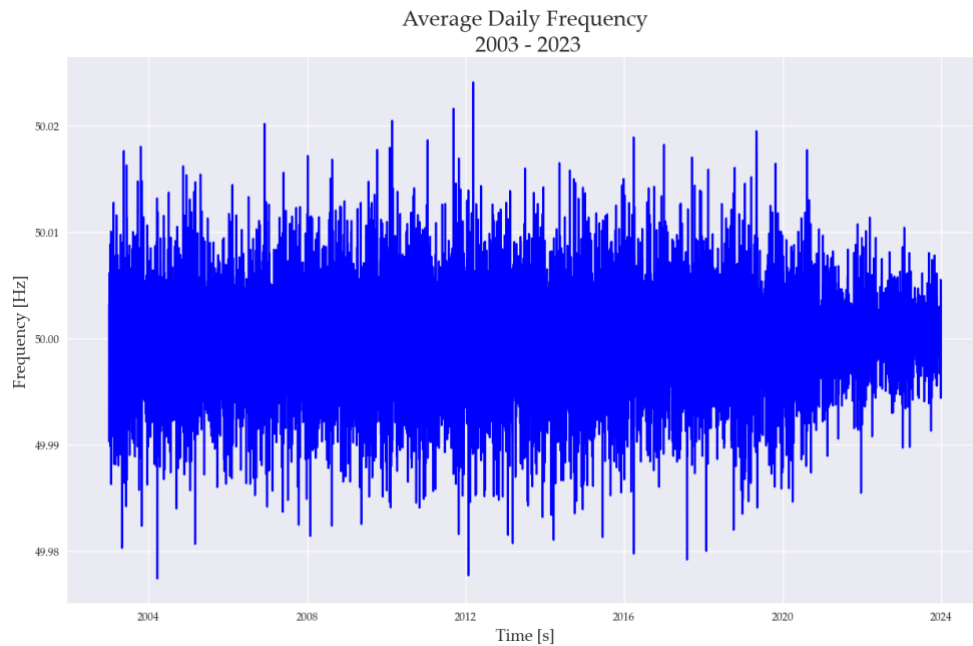


Figure 6: Average daily frequency in period between 2003 and 2023

In addition, Figure 7 and Figure 8 show daily maximum and daily minimum recorded frequency values in the same period. While average frequency values are becoming closer to 50 Hz in the last 4 years as shown in Figure 6, maximum and minimum values are showing a trend of increasing the peak values and decreasing the dip values.

The high peaks in frequency during the last four years in Figure 7 can be a consequence of that. There is no corresponding FFR for over-frequencies, in combination of the risk of large sudden load changes, since year 2020 when large HVDC-links were commissioned. More conclusions on Figure 7 and Figure 8 are later made in Chapter 4.

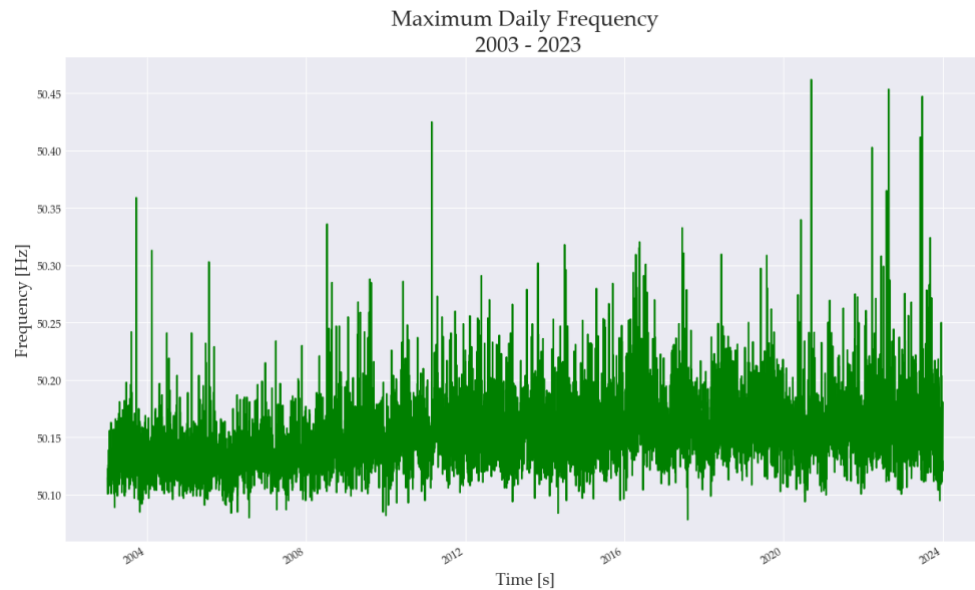


Figure 7: Maximum daily frequency in period between 2003 and 2023

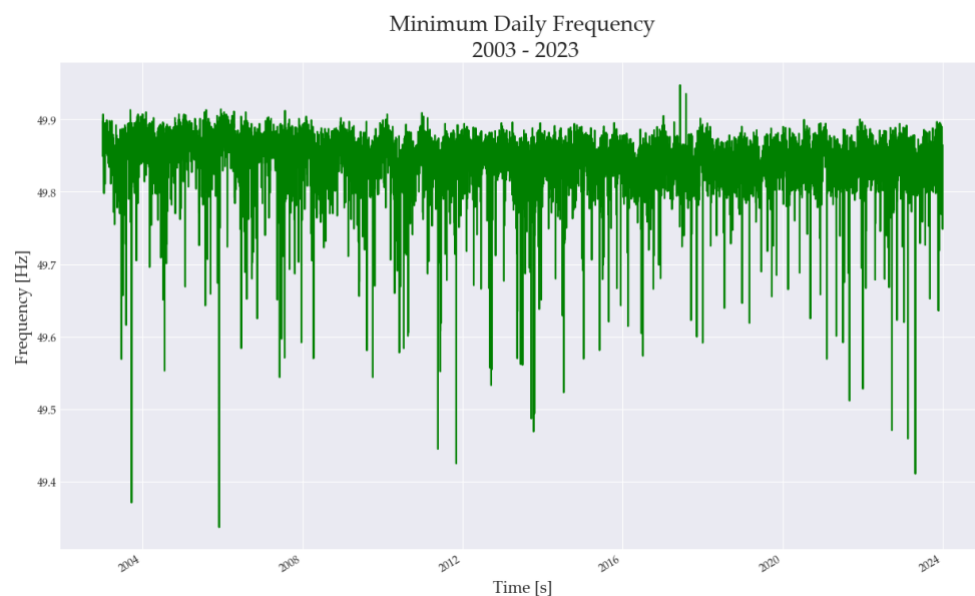


Figure 8: Daily minimum frequency in period between 2003 and 2023

In the last 10 years, the slight trend of deviations becoming shorter in time can be observed, as well as decreasing the value of KPI *minutes outside of frequency range*, see Table 1 and Figure 2.

Figure 9 shows distribution of over- and under-frequency events in the period between 2003 and 2023 according to their duration and type. Due to simplicity of presentation, we only plot events that lasted longer than 10 minutes. During the first 6 years (2003 – 2008) these type of events were shorter in time but became increasingly longer in time and occur more often since 2008, with many deviation

events lasting longer than 15 minutes. The longest interval in which frequency was constantly above 50.1 Hz lasted around 38 minutes in year 2018, see Figure 9.

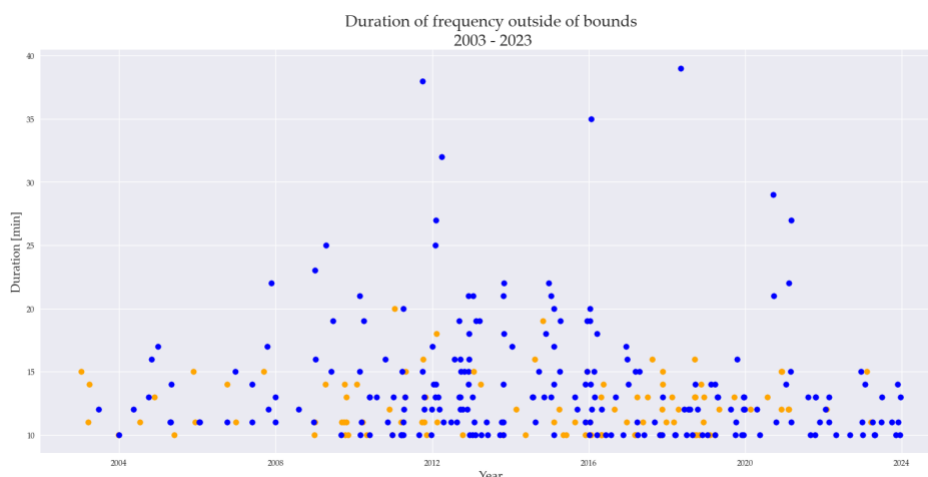


Figure 9: Duration of events when frequency is outside of frequency range ± 0.1 Hz, blue = over-frequency, orange = under-frequency

However, if we observe maximum and minimum values of frequency deviations in Figure 7 and Figure 8, these events might become shorter in time but have higher absolute peak values in frequency. According to Fingrid Frequency Quality reports for the years 2020, 2021 and 2022 [2] [4] [5], most of the disturbances with frequency deviation higher than 0.3 Hz are caused by faults in HVDC interconnectors and nuclear power plants. More details on HVDC interconnectors in the Nordic Power System is given later in section 4. More often, due to HVDC interconnectors exporting, these tripping events today lead to frequencies higher than 50.4 Hz, but this is still well within the level below 51.0 Hz which is the highest required frequency for unlimited time in the Requirement RfG [6].³

The disconnections of nuclear power plants have resulted in even larger frequency dips during the last four years. If the trend of that these dips in frequency becomes larger and whether it is caused by decreasing system inertia is hard to state. In order to do so, each event must be analyzed and for instance; investigate the actual amount of inertia in the Nordic Power System for each dip in frequency, see Figure 8.

Figure 10 shows the mean frequency value for one hour interval, based on data in the period between 2003 and 2023, i.e., it is built upon statistics for in total 184 080 hours. For trend comparison, we also observe the last four years in the database, i.e., the period between 2020 and 2023 which is built upon statistics for in total 35 064 hours.

If we observe the beginning of the hour interval, a significant trend of drop in frequency can be seen. At the end of the hour interval a trend of increasing

³ Only a few large power plants fulfill the RfG [6]. Most of the existing plants are built fulfilling earlier requirements.

frequency can be seen and two minutes before the full hour the frequency is statistically the highest during the whole hour. Some of the reasons influencing this behavior might be the difference in fast rate of change of generating units in comparison with slow loads, as well as behavior of generating units due to market signals and difficulties in forecasting some of the units. We foresee here changes in the behavior of market participants once the market changes from 1 hour intervals of settlements to 15 minutes, as planned during the spring of 2025.

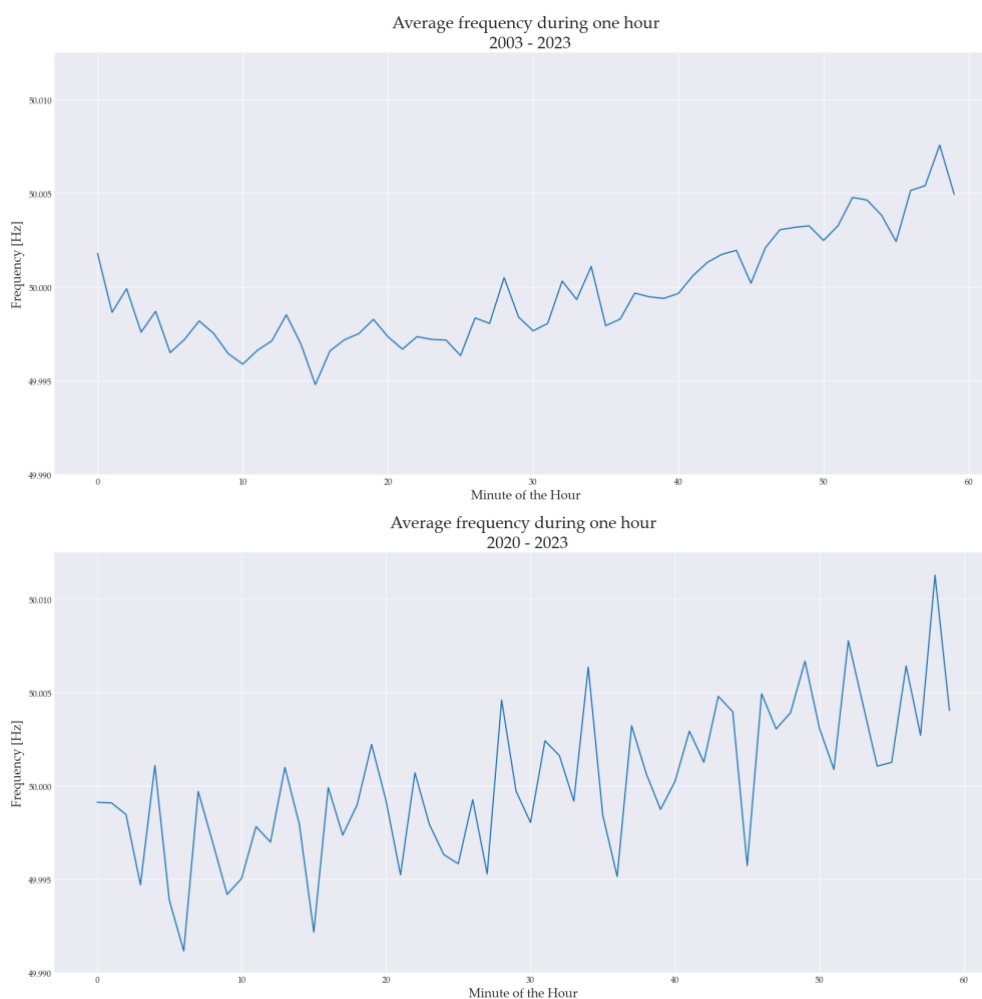


Figure 10: Mean frequency for one hour window for period between 2003 and 2023 (above) and for period between 2020 and 2023 (below)

Figure 11 and Figure 12 show the total number of under- and over-frequency events in the period between 2003 and 2023 and at what time of the day these events occurred.

Under-frequency events occur both during night and day, while over-frequency events occur most often in the morning hours (at 06:00, 07:00, and 08:00 EET/Helsinki Time).

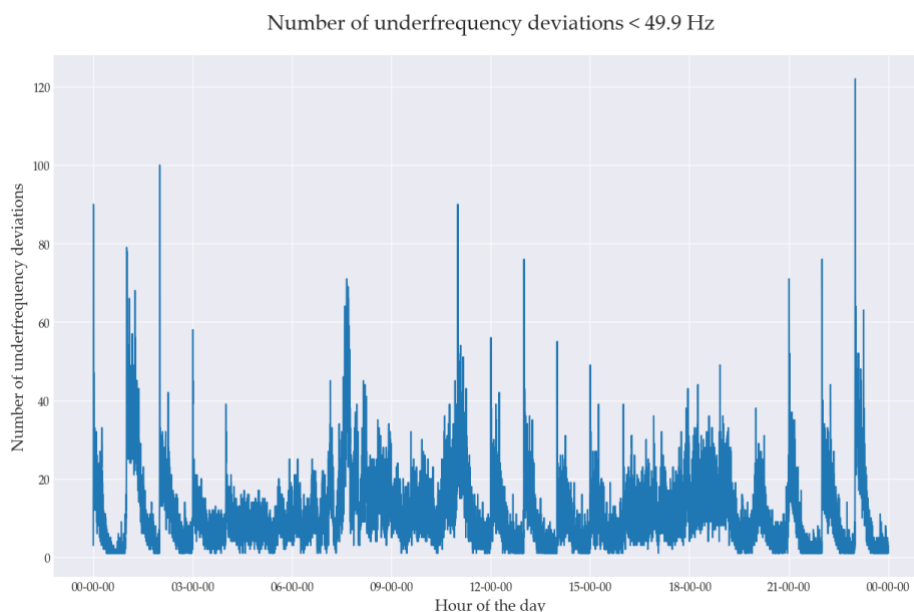


Figure 11: Number of under-frequency events ($f < 49.9$ Hz) in the period between 2003 and 2023 and time of day when they occurred

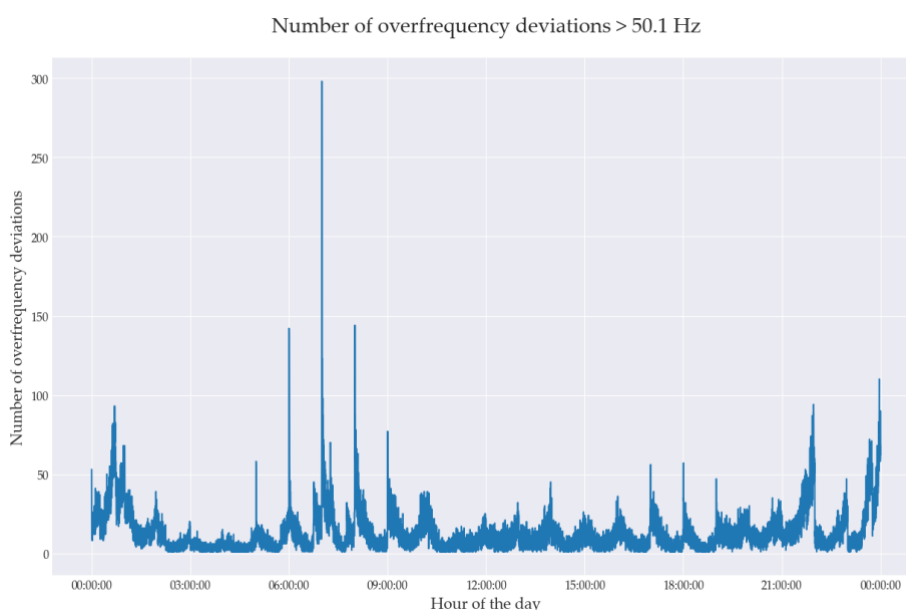


Figure 12: Number of over-frequency events ($f > 50.1$ Hz) in the period between 2003 and 2023 and time of day when they occurred

Within the last twenty-one years, the frequency has been higher than 50.1 Hz at 7:00 in the morning (EET/Helsinki Time) at 300 days which is a clear signal that the frequency quality is worse during large load changes in the morning which happens around the full hours. Under-frequency events most often occur just after the full hour and over-frequency just before the full hour as shown in Figure 10.

2 Investigation of system inertia dependency on nuclear power plants

The inertia in a power system varies over time. This is caused by changes in the load and production pattern on daily, monthly and seasonal level, as well as changes in production mix since each plant provides different values of inertia.

In this work an estimation of the total rotating inertia (originating from observable production) in the Nordic Power System is made from publicly available data during the last eight years (2016 – 2023). From these analyzes it is derived how large part of the inertia comes from nuclear power plants in the Nordic Power System during the operated hours between 2016 – 2023.

The goal of these calculations and estimations is to highlight if there are times throughout the year when the inertia from nuclear power plants is more important. Is there any trend in level of inertia in the Nordic Power System in the last eight years? Can that trend be correlated with the frequency quality that has been analyzed in the previous section?

2.1 DATA SOURCING

The inertia of the Nordic Power System was gathered from public available data from Fingrid [7]. This dataset represents a real-time estimate of the kinetic energy of the Nordic Power System. The data was sampled from 2015-03-27 with a sampling rate of 1 minute.

The value for nuclear inertia has also been gathered for all NPPs in the Nordic Power System. The inertia for each NPP is calculated with regard to the rotating parts of the turbine-generator shaft train, i.e., HP and LP turbine rotors, generator rotor, and exciter rotor. The majority of the inertia values were shared to the project directly by the NPP owners. However, some NPP inertia values were not shared directly to the project due to security reasons. Therefore, the following assumption for those inertia values has to be made:

$$E_{kin} = H * S_r \quad (1)$$

Where S_r is the generator rated power. H is the inertia constant, defined as the time interval during which an electrical generator can supply its rated power only using its kinetic energy stored in its rotating masses. For those values that was shared directly to the project, the inertia values ranged between 5-8 s (per turbine/generator string). According to literature, a typical value for a NPP inertia constant is around 4 seconds [8] [9] [10]. An inertia constant of 4 seconds was therefore used as an assumption for those NPPs that did not directly share their inertia values to this project. It should be noted that 4s is conservative if compared to the inertia values that was given directly from the NPP operators.

2.2 SYSTEM INERTIA ANALYSIS FOR PERIOD BETWEEN 2016 AND 2023

Figure 13 shows average daily inertia value in the Nordic Power System in the period between 2016 and 2023. We observe the seasonal nature of inertia, where inertia levels are lower in the summer and higher in the winter. Since we only look at average daily values of inertia, Figure 13 does not capture daily patterns of inertia change (lower levels of inertia during night, and higher levels of inertia during the day).

Average lower levels of inertia rarely go below 125 GWs and are kept to that season-low level mostly constant during the last eight years. But a slight decreasing trend of average daily winter inertia values (the higher seasonal levels) can be observed during the last eight years of available data, with a slight increase in the winter of 2023.

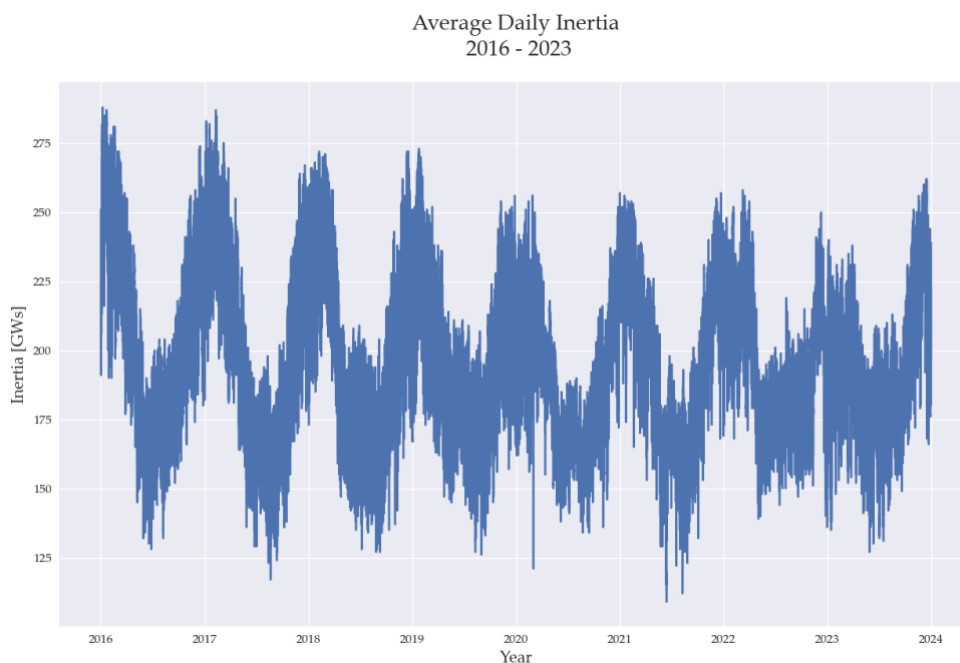


Figure 13: Average daily inertia in period between 2016 and 2023

The trend of decreasing value in total inertia can in one part be connected with the process of decommissioning of nuclear power plants in the Nordic Power System. Figure 14 shows how nuclear inertia varies during the period between 2016 and 2023. Marked in red are points of time when an NPP unit has been decommissioned, and in yellow when a new NPP unit has been commissioned. More details on which exact unit have been decommissioned or commissioned has been given in Table 4 where dates are given when Oskarshamn 1, Oskarshamn 2, Ringhals 1, and Ringhals 2 are decommissioned and Olkiluoto 3 is commissioned.

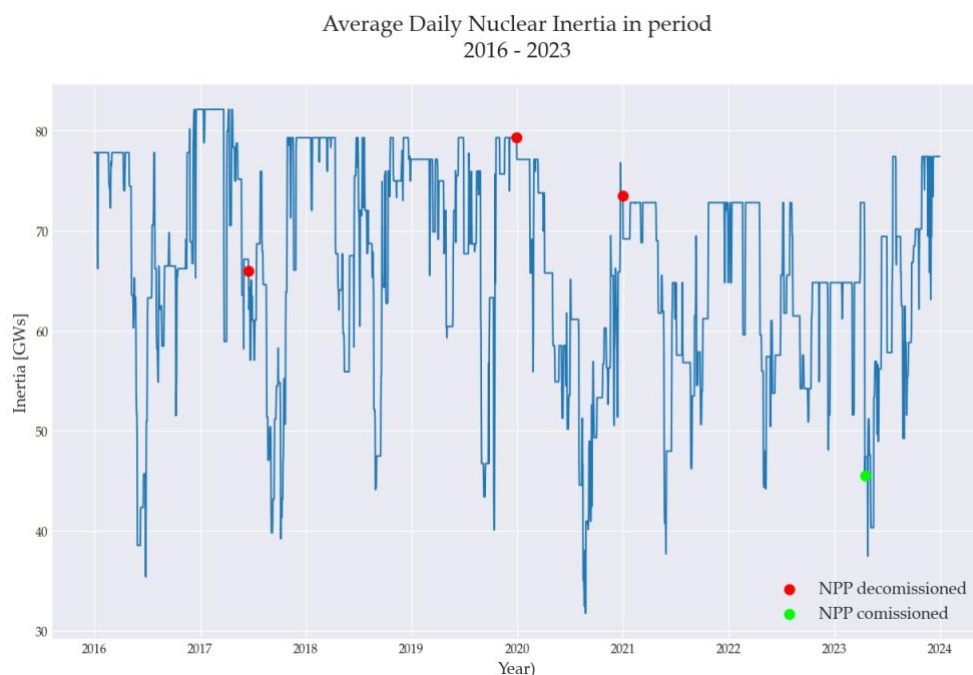


Figure 14: Average daily nuclear inertia during period between 2016 and 2023

Table 4: Commissioned and decommissioned NPPs since 2015

Plant	Date	Status
Oskarshamn 1	2017-06-17	Decommissioned
Oskarshamn 2	2015-10-14	Decommissioned
Ringhals 1	2020-12-31	Decommissioned
Ringhals 2	2019-12-30	Decommissioned
Olkiluoto 3	2023-04-16	Commissioned

In Figure 14 all planned and unplanned trips of nuclear plants in the Nordic Power System is documented for the last eight years. If a plant is load-following during a period, i.e., that the power is partly reduced but it is still delivering power to the grid, the inertia is counted as 100% from that plant since the kinetic energy is still the same even though the produced power is reduced.

In Figure 14 it can be observed how the revisions in the nuclear plants every year reduce the available inertia from about May – September. The low levels of inertia from nuclear goes down to almost the same levels for all summers over the last eight years, around 35 – 45 GWs, even though the total number of NPPs has been reduced with three plants during the same period. This can be also linked with nowadays practice of having only one nuclear power plant on planned outage at the time, which was not a practice earlier.

Although the annual peak levels of inertia coming from nuclear power plants decreased during the period, as per decommissioning schedule of units presented in Table 4, it can be observed in Figure 14 that with the introduction of the new

unit Olkiluoto 3 in year 2023 the annual peak of nuclear inertia is back to almost the same level as before Oskarshamn 1, Ringhals 1, and Ringhals 2 were de-commissioned, see year 2016.⁴

The amount of nuclear inertia seems not to decrease further in the coming decades since at the moment (year 2025) several of the nuclear owners in the Nordic countries are examining lifetime extensions of the existing plants. Nevertheless, there are plans of building new NPPs in Sweden in the coming decades so the nuclear inertia can have passed its minimum in the 21st century during 2020 - 2022.

In addition, we observe that the year 2020 had in general the lowest nuclear inertia of the last decade with a long period of low inertia during summer. However, if we look at frequency quality in Table 1 and Figure 2 it can be seen that the frequency quality level in 2020 is one of the best for the last decade.

In Figure 15 the frequency is shown in green for the last eight years where the four last years are shown with a green bold line. The 8-year average monthly frequency quality is shown with a black graph. The Average monthly system inertia is shown in red graphs with the last four years in red bold lines.

We observe high frequency quality during periods of low levels of inertia during June to October except for the month of May where we can see a peak of KPI in mean monthly *minutes outside of frequency band ± 0.1 Hz*. The inertia level relative to the actual load is lower in May compared to June and July which might affect the frequency quality. The load in May is about 10% higher compared to July. Also, in May often there is spring flood (in Swedish *vårflod*) that can reduce available a-FRR and m-FRR leading to an insufficient situation to bring back the frequency into the frequency interval 50 ± 0.1 Hz.

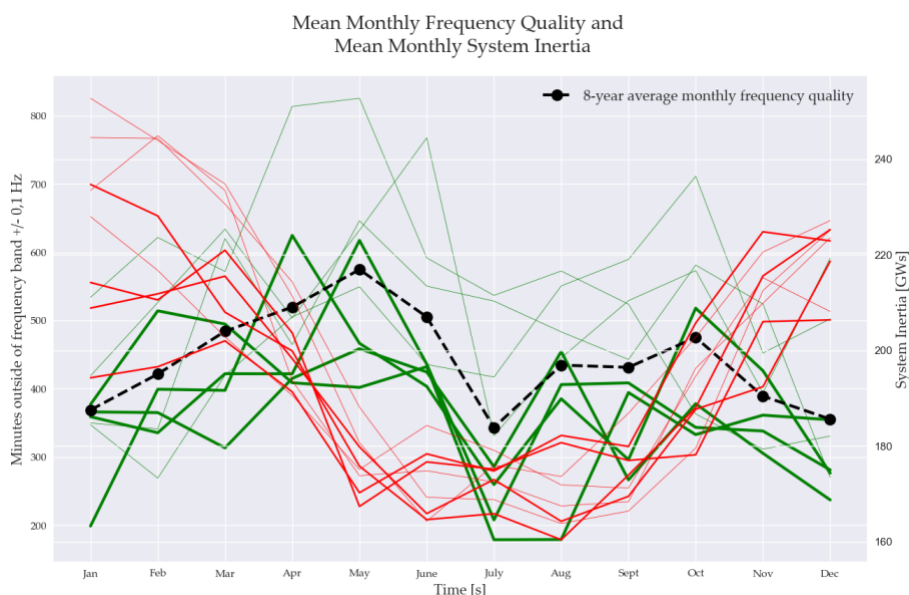


Figure 15: Mean monthly system inertia (red) and minutes outside of frequency bonds (green) in period between 2016 and 2023, with last four years plotted bold

⁴ The de-commissioning of Oskarshamn 2 is not included here since that took place on October 14, 2015, i.e., the year before the studied period.

As per data analysis in this section, we can conclude that there is not any clear correlation between frequency quality and inertia in general nor nuclear inertia (in the sense of the KPI-*"minutes outside of frequency range ± 0.1 Hz"*). On the contrary, we observe that during summer months, when inertia is often very low in the system, frequency quality is better than during other months of the year.

In spite of this it is important to understand that inertia is an important system quantity in case of larger transient events like for instance sudden disconnections of large production units when system inertia supports the power system so that the frequency deviation becomes smaller.

3 Wear and tear of components influenced by grid frequency variations

In this section we aim to identify if frequency deviations are stressful for nuclear power plants, i.e. are they subjected to more wear and tear following a lower quality of the grid frequency? The Nordic nuclear power plants (NPPs) that currently are in operation have to run in accordance with TSO regulations (grid codes). There are however slight differences between the Nordic NPPs as can be seen in Figure 16 and Figure 17 below [11] [12] [13].

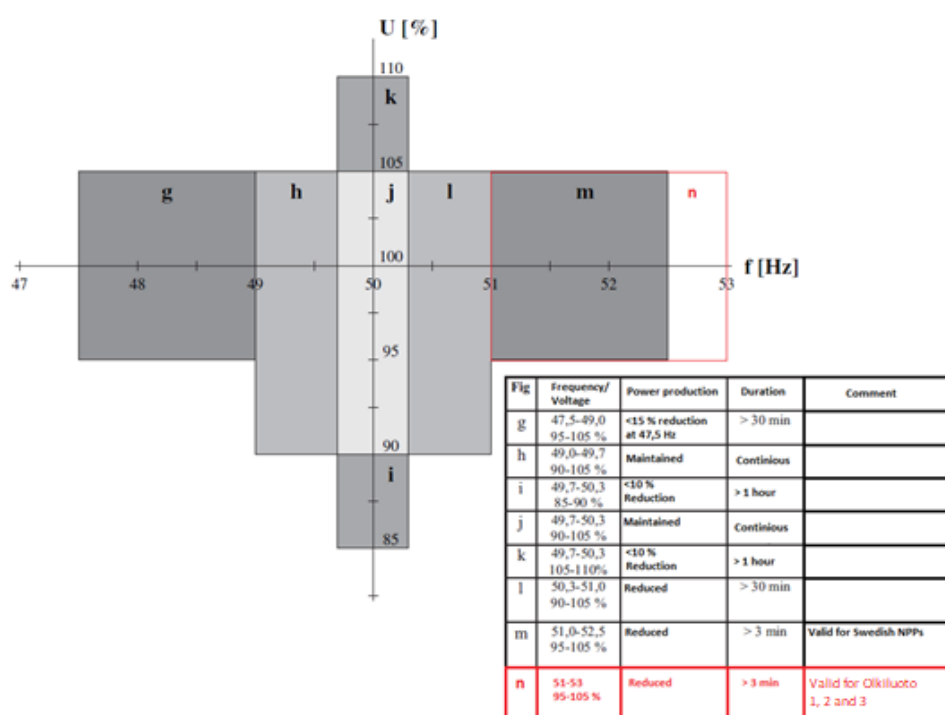


Figure 16: Grid code regulations for operating voltage and frequency range. Difference in Swedish and Finnish regulations are marked in red. Picture taken from SvKFS 2005:2. Note: Swedish NPPs that didn't have any significant power upgrades after 2006 follows older grid codes. The older grid code regulations for operating voltage and frequency ranges are however similar to SvKFS 2005:2.

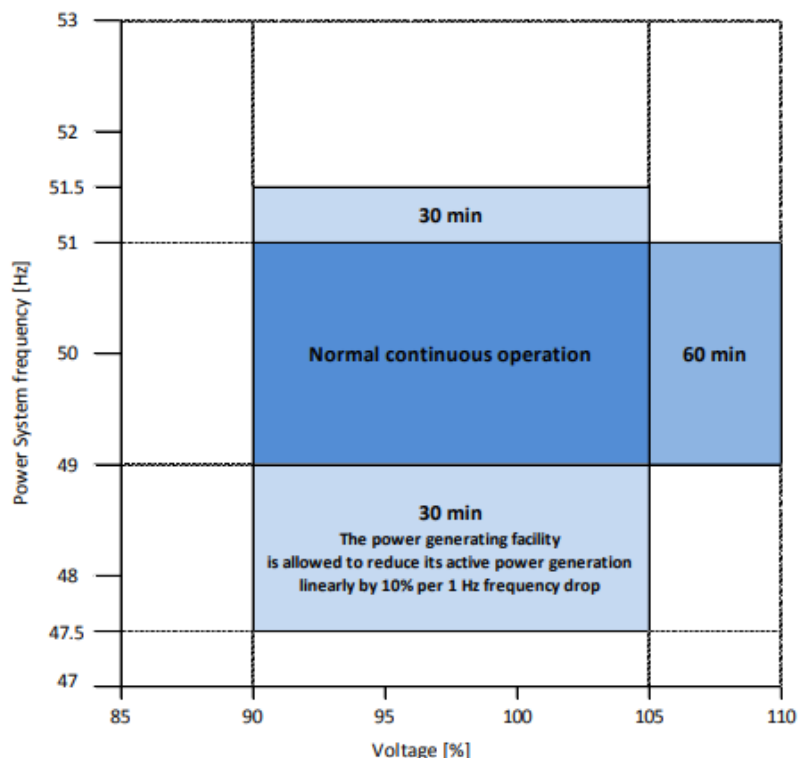


Figure 17: Grid code regulations for operating voltage and frequency range. This regulations are valid for Loviisa 1 and 2. Picture taken from Fingrid VJV2018.

As can be seen in Figure 16 and Figure 17, the Nordic NPPs have to run continuously in the range of 49.0 – 50.3 Hz. Within the ranges of 47.5 – 49.0 Hz, 51.0 – 52.5 Hz (Sweden) and 51.0 – 53.0 Hz (Olkiluoto), the NPPs have the possibility to run with reduced output power at a limited time duration. If the grid frequency is outside of the 49.0 – 50.3 Hz-range at a longer time specified by the durations in Figure 16 and Figure 17, the NPPs have the possibility to enter house load operation.

In the case of significant power upgrades or new NPPs, the NPP owner has to follow the EU Commission Regulation 2016/631 (often called the RfG). The RfG requirements for operating frequency are slightly different, where the NPPs are required to run continuously in the range of 49.0 – 51.0 Hz [6].

Theoretically, the electrical equipment in a NPP should experience some kind of wear when running at a frequency other than the rated frequency. Can we expect a shortened lifetime for a specific electrical component in a NPP after a grid frequency deviation with regards to both magnitude and duration of the deviation? This study is taking a deeper look at rotating electrical machines, power converters, power transformers and instrument transformers. They are further discussed in the following sections.

3.1 ROTATING ELECTRICAL MACHINES

This group includes all rotating electrical machines according to IEC 60034-1 and IEC 60034-3 [14] [15]. The standards specify requirements regarding rating and performance for AC generators and motors, from now on described as *standard AC machines*. For a standard AC machine operating at rated power, combinations of voltage and frequency variations are classified as being in either in zone A or zone B, according to Figure 18 below. Extended operation in zone B is not recommended and may lead to reduced machine life due to temperature effects, vibrations and magnetic pull [14].

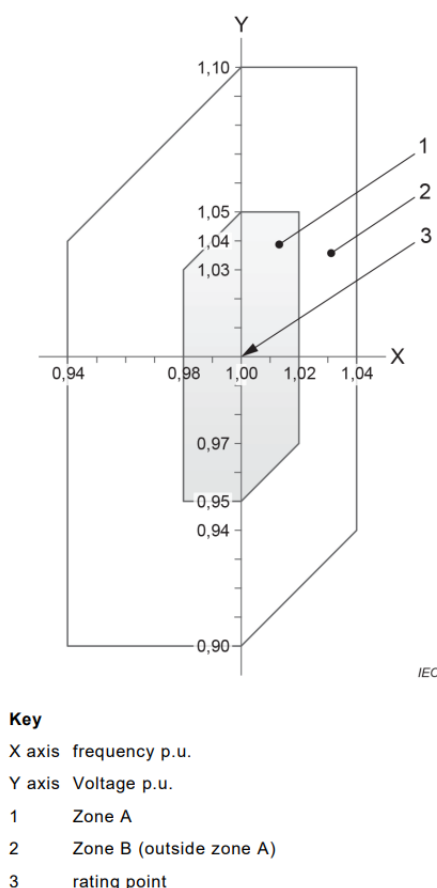


Figure 18: Voltage and frequency limits for standard AC machines. Source: IEC 60034-1

However, this recommendation applies to *extended* operation in zone B. For a standard AC machine rated at 50.0 Hz, this means operating under 49.0 Hz or over 51.0 Hz. According to our research, there have been no events in the Nordic synchronous grid since 2002 where the frequency was outside 49.0 Hz or 51.0 Hz.

3.1.1 Example: Operating induction motors over/under their rated frequency

This example is valid for centrifugal fans and pumps driven by induction motors in the low slip region (i.e. the linear electrical torque-speed region). If the grid frequency f increases, the motor current will increase due to a higher load demand.

The required power P is linearly dependent on the torque M and the angular velocity ω of the axis. The torque M is in turn quadratically dependent angular velocity ω . This means that the required shaft power is cubically dependent on the shaft speed, and therefore cubically dependent on the grid frequency. As a result, the increased operation current due to increased grid frequency can be written as [16]:

$$P = \omega M \xRightarrow{M \propto \omega^2} P \propto \omega^3 \Rightarrow P \propto f^3 \Rightarrow \frac{P_1}{P_0} \propto \left(\frac{f_1}{f_0}\right)^3 \Rightarrow \frac{I_1}{I_0} \propto \left(\frac{f_1}{f_0}\right)^3 \quad (2)$$

Where I_0 and f_0 are the rated current and frequency for the motor, and I_1 are the motor current at frequency f_1 . The relationship between motor current (at constant voltage) and grid frequency is shown in Figure 19.

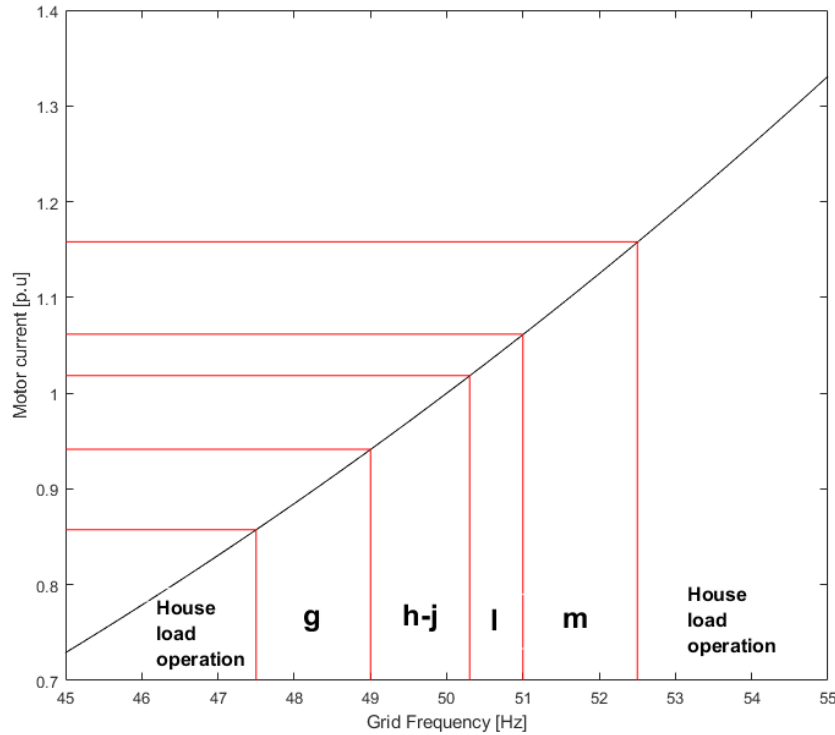


Figure 19: Motor current as a function of grid frequency (at constant voltage). This example is valid for centrifugal pumps and fans driven by an induction motor. The areas correspond to SvKFS 2005:2 robustness for grid disturbances.

Operating at over-frequency

If the operating current is higher than the rated current, you could expect some kind of wear due to increased winding temperatures. According to current grid codes, the motors should be able to run continuously up to 50.3 Hz. This implies an increased operation current of $(50.3/50)^3 \approx 2\%$. However, the NPP owner have

compensated for this by over dimensioning the motor such that it can operate continuously at 50.3 Hz without triggering the overcurrent thermal protection [16].

If the motor is operating in zone “m” in Figure 19, it is operating outside of the design limits according to IEC 60034-1. However, for zone “m” the NPP has the possibility to enter house load operation after 3 minutes, which should protect the motor from heat related damage. In the meantime, NPPs that operate according to the RfG should run at least 30 minutes with a grid frequency between 51.0-51.5 Hz before going to house load operation. This will indeed be more stressful to the motors. However, the overcurrent thermal protection should work as intended and protect the motors from any heat related damage.

Operating at under-frequency

Both SvKFS 2005:2 [13] and the RfG [6] have the same requirements for under-frequency operation. Figure 16 and Figure 17 shows that the NPPs should run at least 30 minutes with a grid frequency range of 47.5 – 49.0 Hz before it has the possibility to go into house load operation. At stable voltage, Faraday's law of induction states that the air gap flux density of the motor will increase linearly with reduced grid frequency.

If the air gap flux density is increasing, you could expect a reduced power factor and increased iron core losses [17]. If the magnetic flux is assumed to be purely sinusoidal, the iron core losses p_{Fe} can be expressed as [18]:

$$p_{Fe} = p_{hyst} + p_{ec} + p_{exc} = C_{hyst}f\hat{B}^2 + C_{ec}f^2\hat{B}^2 + C_{exc}f^{1.5}\hat{B}^{1.5} \quad (3)$$

Where p_{hyst} , p_{ec} and p_{exc} are iron losses mainly in the stator due to hysteresis, eddy currents and excess losses respectively. $\hat{B}$ denotes the peak value of the flux density of the material and f is the frequency of the rotating magnetic field (i.e. the grid frequency). The coefficients C for each term are dependent on the magnetic properties of the material.

In the worst-case scenario, the NPP has to run with a grid frequency of 47.5 Hz for at least 30 minutes. A 5%-reduction of the grid frequency means that the air gap magnetic flux of the motor will increase by 5%. It is obvious from eq. 3 that iron losses due to eddy currents and excess currents are negligible compared to hysteresis when the grid frequency is reduced. The majority of the increased iron losses will therefore be due to hysteresis effects. A 5% drop in grid frequency would then increase the iron core losses due to hysteresis by approximately $0.95 * 1.05^2 \approx 4.7\%$. It should be noted that this is a rough estimation.

3.2 POWER CONVERTERS

This group includes all types of semiconductor power converters covered in SS-EN 60146-1-1 [19]. The standard specifies requirements for the performance of rectifiers, inverters, DC/DC converters and AC/AC converters (often called frequency drives). The equipment that may be affected by deviations in the grid

frequency (i.e. connected to the main grid) in this case are rectifiers and frequency drives. There is, however, no mention in the standard that states a specific range for the rated input frequency.

It is the manufacturers responsibility to specify in the datasheet what input frequency range their products are rated for. Running the device outside these limits is not recommended and could possibly shorten the designed lifetime. One commonly used frequency drive in NPPs is the ABB ACS880 [20]. According to the datasheet, the rated input frequency range is $\pm 5\%$. For a rated frequency of 50.0 Hz, the rated input frequency range is 47.5 – 52.5 Hz. This is in line with the grid code regulations for operating voltage and frequency ranges.

3.3 POWER TRANSFORMERS

This group includes three-phase and single-phase power transformers with ratings over 1 kVA for single-phase and over 5 kVA for three-phase transformers according to IEC 60076-1 [21]. One possible fault due to grid frequency deviations is called *overfluxing*. If the magnetic flux density of the transformer increases to critical levels, the core losses will increase which in turn will lead to overheating. The magnetic flux density is directly proportional to the induced voltage and inversely proportional to the frequency [22].

IEC 60076-1 specifies what frequency and voltage a transformer shall be capable of running at rated power and rated cooling conditions without damage under conditions of overfluxing. The value of voltage divided by frequency (V/Hz) should not exceed the corresponding value at rated voltage and frequency by no more than 5 %. One example of this requirement is shown below in Figure 20. If the transformer operates at rated voltage and power, the requirement simplifies to

$$95\% \leq \frac{f_r}{f} \times 100 \leq 105\%$$

Where f_r is rated frequency, and f is the grid frequency. This means that the transformer should be capable of operating under the influence of overfluxing between a frequency range of 47.5 – 52.5 Hz (at stable voltage). This is in line with the grid code regulations for operating voltage and frequency ranges.

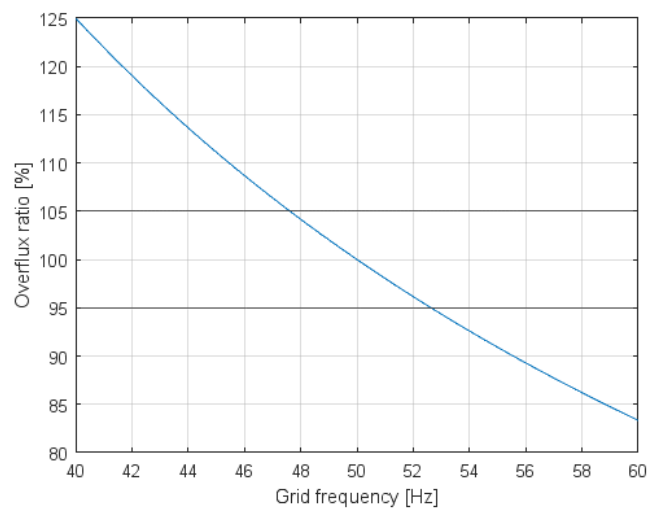


Figure 20: Deviation of Voltage and frequency quotient (overflux ratio) at rated voltage and varying grid frequency.

3.4 INSTRUMENT TRANSFORMERS

This group includes Instrument Current Transformers and Instrument Voltage Transformers. If an instrument transformer (IT) operates at other frequencies than they are rated for, an influence of the leakage inductance at the secondary winding appears. This will increase the total burden of the IT, which leads to increased induction at the IT core and therefore increasing the measurement errors [23].

However, the measurement errors appear at several orders of magnitude higher than the fundamental frequency. One example for an instrument voltage transformer (IVT) is shown below in Figure 21. It is obvious that the IT measurement errors due to disturbances in the grid frequency is not relevant. The measurement errors may be relevant in local power grids with high amounts of voltage and current harmonics, but that is out of scope for this project.

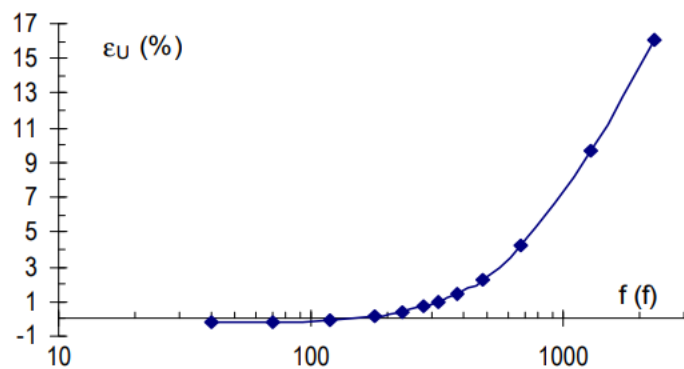


Figure 21: Frequency dependence of ratio error of an IVT. Source: [23]

3.5 INTERVIEWS WITH NPP OPERATORS

3.5.1 Summary of interviews

Interviews were conducted with NPP operators that operate as part of Nordic Power System during September and October, 2024. Each interview lasted 90 minutes and aim of interviews were to get collect information regarding following:

- Frequency of NPP tripping, trends and causes over the last decades
- Correlation between equipment wear and tear and frequency quality

Summary of all interviews is given in Table 5.

Table 5: Summary of interviews conducted with NPP owners during September and October 2024

Question	General summary
How often does the plant trip per year? Reasons?	One NPP operator reports between 0 - 1 time per year due to external grid. One NPP operator reports trips have become more common during the last years. Trips are seldom related to grid faults, and, if they are, it is usually due to voltage, not frequency.
Is there any trend in the recent decade (increased/decreased frequency of tripping)?	A majority of the NPP operators report that there is no decreasing or increasing trends in the last decade, it is quite stable. However, one NPP operator says that there are less stops and one NPP operator reports there are more stops during the last two years (2023-2024).
Has NPP ever tripped because of frequency deviation/dip?	For the last two decades, no NPP operator has reported any trips due to grid frequency deviations.
What kind of events have influence on wear and tear of components (voltage deviations, frequency deviations, etc.)?	Frequency deviations have not been recognized as a cause of wear and tear on equipment. Some NPP operators report limited knowledge on the topic and feel they cannot answer the question at the moment. Some additional causes of wear and tear are reported, i.e. harmonics and voltage disturbances. One NPP operator believes that there might be a negative impact of load following on generators.
What components are more sensitive to frequency deviations than others?	One NPP operator raises concerns of higher wear and tear of the main generator in case it operates close to outer regions of the capability curve combined with large frequency variations.
How does a plant react to frequency deviations? Are there machines that depend on grid frequency (speed regulated)?	There are components that are frequency dependent, for example electrical motors. Some NPP operators report that they oversize their motors so they can run continuously at higher frequencies.
Is there a difference between older and newer equipment in terms of wear and tear?	Mixed reports from different NPP operators. They list the following: - Quality and lifetime issues with modern relays - More vulnerable main generator rotor design in older equipment - Greater margins for older equipment - Generally, lifetime of new equipment is shorter

Is there any impact on life expectancy of components due to grid frequency deviations?	Generally, NPP operators do not link wear and tear with grid frequency deviations. One NPP operator mentions that simultaneous and long-lasting (or frequent) frequency and voltage variations will reduce the length of life of the main generator.
How much do you maintain your components (during revision or more often)?	Yearly maintenance. Each component has its own maintenance schedule.

3.5.2 Interview conclusions and outlook

In general, the NPP operators do not report any experience with wear and tear caused by grid frequency deviations. Nevertheless, they are interested in learning if there might be any wear and tear issues caused by grid frequency deviations.

Regarding NPP tripping, there are differences between the plants in the number of disturbances, as well as recent trends. During the last two decades, some NPP operators report seldom trips, while others report trend of tripping becoming more often. If those trips are caused by grid faults, it is usually due to voltage, not frequency disturbances.

Therefore, more concern is raised about grid voltage disturbances impact on wear and tear of equipment, which might be of interest for future work. For example, voltage variations in a grid close to one NPP is compensated for by the control of the main NPP generator. This control is always active and implies variations of the field current in the rotor. Such variations cause additional thermal wear and tear.

For the future outlook, some NPP operators report concern that the increased complexity of the Power System will imply more frequent blackouts, and such events will include frequency or voltage deviations which may be outside the current grid requirements. In addition, NPP operators are concerned about the increased amount of inverter connected production and are interested in whether it can create problems in the existing power plants production environment.

To conclude, analysis presented in Figure 7 shows that frequency levels have peaked above 50.4 Hz only six times during the last two decades indicating that the situation is still far away from critical levels of 51.0 Hz, as described above. In total, frequency has been higher than 50.3 Hz only for a total of about 2 minutes and 40 seconds during the last 21 years and these time intervals are still not significant to pose a high level of risk on the equipment.

4 Analysis of current and future trends in system services in the Nordic Power System

The goal of this section is to examine existing technologies and methods to stabilize the grid, changes in regulations and other future requirements or changes in the energy mix that may affect the Nordic Power System frequency quality.

4.1 NORDIC POWER SYSTEM CHANGES

During the 21st century intermittent power production, interconnectors to other power systems, new system services, and reduction of inertia has taken place in the Nordic Power System. Therefore, in the beginning of this section, we document the development of intermittent production, interconnectors, and new system services.

4.1.1 Intermittent generation

Intermittent generation, mostly wind and solar, has been increasing in installed power since the beginning of the 21st century and changed the energy mix of the Nordic Power System. Figure 22 and Figure 23 show how the energy mix in the Nordic Power System has changed in the period between 2003 and 2023.

Nowadays (2023), intermittent production counts for almost 20% of the total energy production on a yearly basis in the Nordic Power System, while it was almost non-existent at the beginning of the century, see the green and yellow fields in Figure 22 and its share in Figure 23.

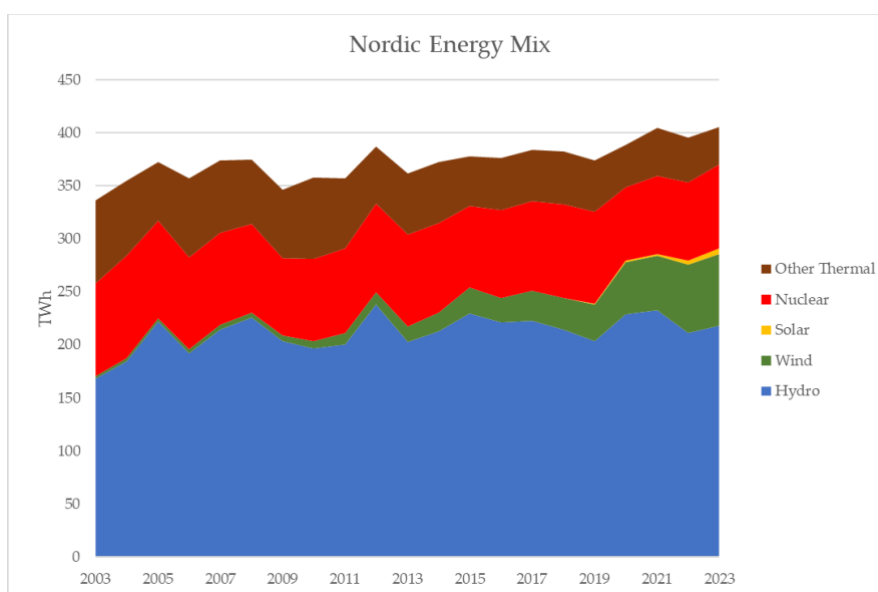


Figure 22: Energy production in the Nordic Power System in the period between 2003 and 2023

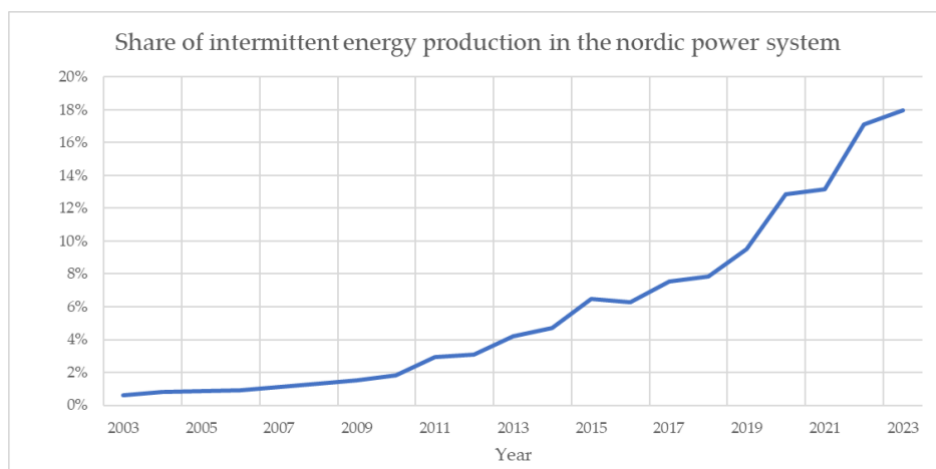


Figure 23: Nordic intermittent energy production in the period between 2003 and 2023

Figure 24 presents monthly wind production in Sweden between year 2003 and 2023. We can observe the increased trend of wind power production and also its seasonal behavior.

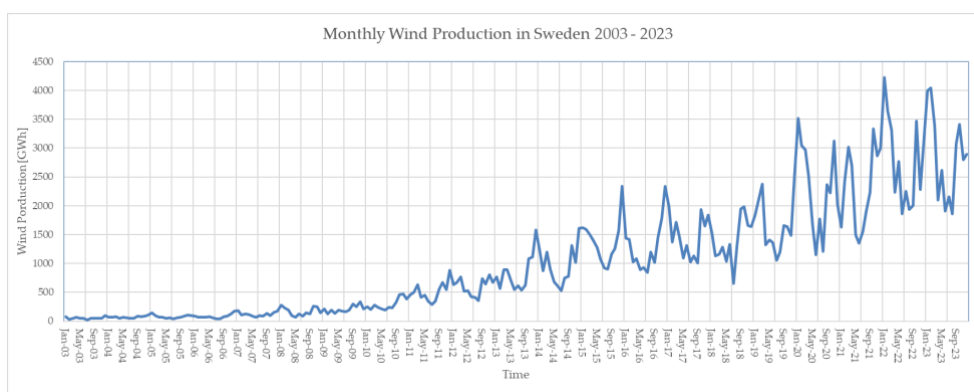


Figure 24: Monthly Swedish wind power production [GWh].

Further on, in Figure 25 we observe the pattern from Figure 24 in wind production in Sweden, with the yearly peaks occurring during the winter months, most often in January and December, and it never happens during the spring and summer months (March – September). Here in Figure 25, the definition of peak is which month during a year the wind power production has been the highest. In the Figure 25 we can see that nine of the twenty-one years between 2003 and 2023 have had the highest monthly wind production in December. Six of the twenty-one years have had the highest monthly wind production in January.

We cannot see any connection between high amounts of wind power and low frequency quality (in the sense of the KPI-“minutes outside of frequency range ± 0.1 Hz”) since during the months of high wind power production the grid frequency

shows a better frequency quality, see the green curves in Figure 15, compared to the months with less wind power production.

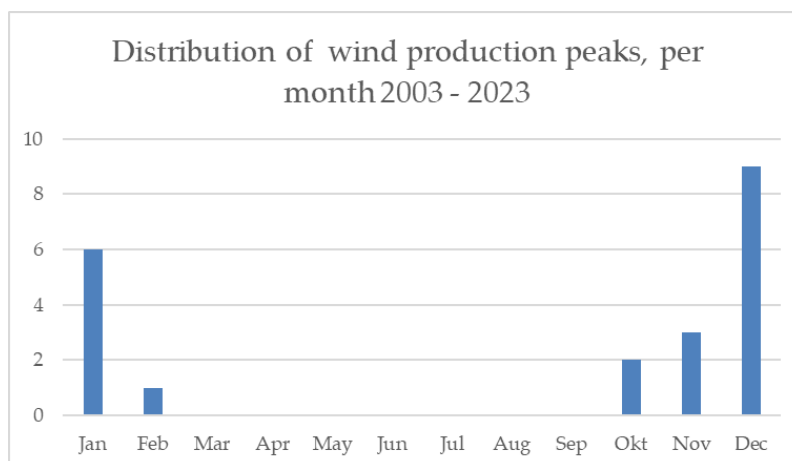


Figure 25: Distribution of number of wind production peaks in Sweden, per month, between 2003 and 2023.

4.1.2 HVDC interconnectors

Current HVDC-links that connect the Nordic Power System with other synchronous systems in Europe are presented in Table 6 and Figure 26.

In Table 6 we can see that during the 21st century the Nordic Power System has been much more interconnected with the close-located synchronous areas Great Britain, Baltic Countries, and Continental Europe.

Table 6: List of HVDC interconnectors connecting the Nordic Power System with other synchronous systems in Europe [24]

Name of HVDC link	Connection points	Year of Commissioning	Installed power (MW)
Skagerrak	NO2 <-> DK1	1993	1000
Baltic Cable	SE4 <-> DE	1994	600
Kontek	GER <-> DK2	1995	600
SwePol	SE4 <-> PL	2000	600
Konti-Skan	SE3 <-> DK1	2008	715
NorNed	NO2 <-> NL	2008	700
Storebelt	DK1 <-> DK2	2010	600
Estlink	FI <-> EE	(2006) 2014	(350) 1000
NordBalt	LT <-> SE4	2016	700
NordLink	NO2 <-> DE	2020	1400
North Sea Link	NO2 <-> GB	2022	1400
Vyborg	FI <-> RU	1984. Out of operation since May. 2022	1300

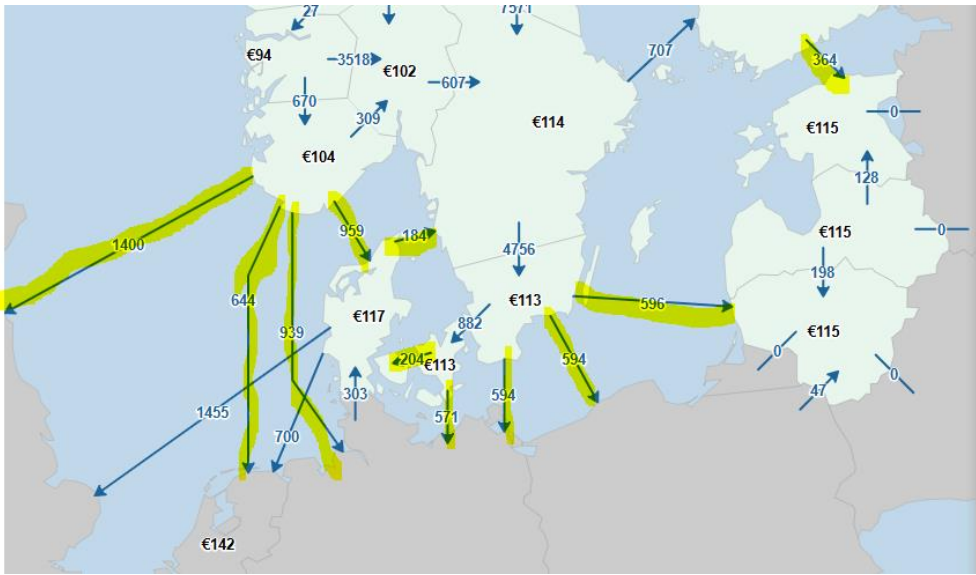


Figure 26: Geographical position of HVDC interconnectors connecting the Nordic Power System with other synchronous systems in Europe (marked in yellow) [25]

4.1.3 Frequency control reserves in the Nordic Power System

The frequency control reserves in the Nordic Power System can be divided into three subgroups [26] and they are illustrated in Figure 27:

- Frequency Containment Reserves (FCR) - fast power activation that activates automatically and proportionally in response to a deviation in frequency within certain intervals. FCR for normal operation (FCR-N) stabilizes fluctuations between production and consumption in normal operation in the frequency interval 50 +/-0.1 Hz and FCR for disturbances (FCR-D) stabilizes large power imbalances that may occur.

FCR-N is fully activated at 49.9 Hz with 600 MW of FCR-N delivered to the grid.

- Frequency Restoration Reserves (FRR) - FRR is not as fast as FCR. FRR is divided into two parts, automatic FRR (a-FRR) and manual FRR (m-FRR).
- Fast Frequency Reserve (FFR) is utilized in situations with low levels of kinetic energy (inertia) in the Nordic Power System in combination with a risk of high imbalances. It is activated if the frequency is decreasing rapidly and that the frequency is at the same time below 50.0 Hz, i.e., FFR is only activated in situations with under-frequency and not activated in situations with over-frequency. FFR was introduced in year 2020 and it is asked for around 100 hours of the full year and is only activated when necessary.

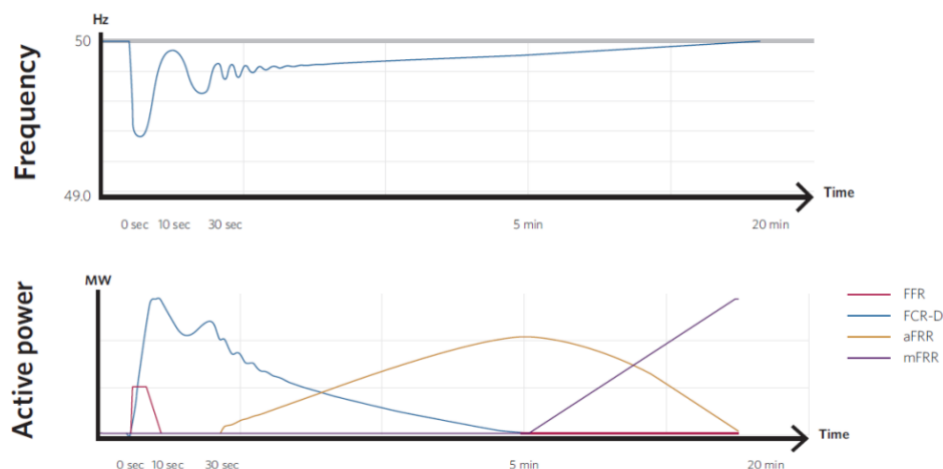


Figure 27: Example of a large frequency disturbance and illustration of the different reserve activations [26]

4.2 INTERVIEWS WITH TRANSMISSION SYSTEM OPERATORS

4.2.1 Summary of interviews

Interviews were conducted with the Transmission System Operators (TSOs) that operate parts of the Nordic Power System and have nuclear plants in their respective grid, i.e., the Swedish TSO Svenska Kraftnät and the Finnish TSO Fingrid. The interviews were held during September and November 2024 and each interview lasted 90 minutes. The aim of the interviews were to collect information regarding the following:

- General frequency quality and trends in the Nordic Power System
- Frequency control services in the Nordic Power System,

A summary of all interviews is given in Table 7.

Table 7: Summary of interviews conducted with two TSOs during September and November 2024

General comment on frequency quality in the Nordic Power System?	Frequency quality can be understood differently. It is dependent on inertia and inherent system capabilities. The long-term trend is that the inherent capabilities are not there, especially during summer nights due to decommissioning of NPPs and more non-synchronous generation. Due to that, new frequency control services are entering the market.
How have frequency services changed since 2001?	New products are a-FRR (approx. last 10 years) and FFR (since 2020). Neither these two have replaced the other system services that have existed before but have been introduced as a complementary service. FFR today replaces lack of inertia in the system, during sunny and windy summer days in continental Europe, when imports are

	high, and inertia in the system is low, mainly between May - September.
Is there an improvement in frequency quality when FFR is active?	FFR can be used anytime during the year but is asked for typically between May and September. It improves the frequency quality during large disturbances, I.e., the nadir (the lowest frequency value) is higher. FFR protects the grid from low frequencies during large events, however it does not affect the KPI of frequency outside 0.1 Hz.
Can you see any changes in frequency quality with new participants entering the market?	TSOs need to prepare for both scenarios with long-term nuclear with lots of inertia build and with scenarios of high level of intermittent generation and little inertia. Decisions will be made as changes in the system happen and based on scenarios. The TSOs are working on being ready for each possible scenario. There will be new and improved frequency stabilizing services, for instance Dynamic FFR that will most likely be introduced in the coming years. Still, in order to keep the system stable, the lower level of inertia for the whole Nordic Power System should as of today (2024) not go below approximately 100 GWs. The new frequency stabilizing service Dynamic FFR is expected to handle even lower levels than 100 GWs in the future Nordic Power System.

4.2.2 Interview outlook and conclusions

Frequency peaks

During the last four years new larger HVDC links with very high capacities have been established between the Nordic countries and other synchronous grids in Europe. NordLink was commissioned in 2020 with 1400 MW of transmitting capacity between NO2 (Norway) and DE (Germany) as well as North Sea Link that was commissioned 2022 with 1400 MW of transmitting capacity between NO2 (Norway) and GB (Great Britain), see Table 6.

These large HVDC links are components of a larger size connected to the Nordic countries. Nowadays there are limiting regulations in their normal operation concerning the sizes of changes in transmitted power of the HVDC-links.

However, when these links suddenly trip, they cause very large system events. Since a majority of the time the HVDC-links are exporting energy from the Nordic Power System, this results in high over-frequencies in the Nordic Power System.

If we observe maximum and minimum values of frequency deviations in Figure 7 and Figure 8, these events might become shorter in time because of the lower KPI of frequencies outside of ± 0.1 Hz, but they have higher absolute peak values in frequency during the last four years.

A reason for the frequency peaks in Figure 7 is, as mentioned above, trips in exporting large HVDC links. For instance, the three highest frequency peaks during 2022 resulted in the frequency peaks listed in Table 8.

Table 8: Tripping information from the three highest frequency peaks during 2022. Values for the frequency peak in parenthesis is from reference [2].

Date	Frequency peak (Hz)	Delta frequency (Hz)	Exporting power (MW)	Inertia in the Nordic Power System (GWs)
2022-03-22	50.40 (50.44)	0.44	1410	239
2022-08-02	50.37 (50.39)	0.38	958	188
2022-08-21	50.45 (50.52)	0.46	1410	178

Delta frequency in Table 8 is the difference between the peak frequency and the initial frequency just before the event took place.

In Table 8 we can see that the highest delta frequency (0.46 Hz) happens when the exporting power was 1410 MW and the inertia in the Nordic Power System was not more than 178 GWs on August 21, 2022. This indicates that the amount of inertia is important for reducing the sub-sequent frequency deviations, in this case a frequency peak. A frequency peak of 50.52 Hz is however still well inside the RfG requirement of maximum 51.0 Hz, see [6].

Here it can be important to comment that, frequency services for over-frequencies such as FFR or future Dynamic FFR are believed to be able to counteract large frequency deviations related to large events, however FFR is not activated as of today (2025) for over-frequencies. It can therefore be beneficial to develop such frequency products also for over-frequencies in periods of low inertia in the Nordic Power System that can complement other functionalities such as Limited Frequency Sensitivity Mode – Over-frequency (LFSM-O).

A new record in transmitted energy of Nordic HVDC-links was reached in 2023 with a total of 76 TWh. This leads to the conclusion that the behavior of these dominating components today has a large influence on the power system and its frequency quality [27]. The high frequency peak events are a new characteristic of the Nordic Power System.

The peaks in frequency are however still below the requirements in the RfG requirement which allows frequencies of up to 51.0 Hz, as shown in Figure 17 and [6]. It is believed that these high peaks in frequency will also be present in the future because of these recently established large HVDC links.

Frequency dips

In Figure 8 we can see the number of short frequency dips. The majority of these dips are caused by tripping of nuclear power plants, and during recent years also HVDC-links that trips when importing. There are also some other grid events causing the frequency dips. These dips have been present during the last decades and will continue to do so.

A system service that is used to reduce the magnitude of these dips in frequency is today (2025) FFR and it has shown that FFR is a very effective solution to support the system in case of low levels of inertia when large production units and importing HVDC links trips.

Long durations of high frequencies

In section 1, we show that there are several events with long duration when the frequency is higher than 50.1 Hz. Also, it is shown that these events happen often during nights and around the full hour. The longest interval in which the frequency was constantly above 50.1 Hz lasted around 38 minutes, see Figure 9.

Frequency is often high in the morning hours. One reason for this is that during these events the amount of down regulating capacity in m-FRR is not sufficient. Circumstances that are impacting these frequency conditions include very windy conditions, low prices, erroneously forecasting, high import power from Continental Europe, and low load. At such circumstances the controllable power such as hydropower and thermal power is producing less because of the low electricity price which leads to a lack of m-FRR. This is a consequence since it is mostly hydropower and thermal power that deliver m-FRR. Therefore, it is of importance to expand the volumes of m-FRR in the future to include also other production units, for instance, potentially also wind power.

Duration of low frequencies

In Figure 9 we can see that the number and the periods of low frequencies are constant during the last two decades, i.e., the production mix is changing, but new frequency services have been applied to the Nordic Power System. These services have been effective at keeping the same amounts of low frequencies and their durations at the same level as before. During the last four years (2020-2023) the number of events with low frequencies and their duration has even been reduced. Products like m-FRR up and a-FRR up have improved the frequency quality and today we can see fewer long durations of low frequencies, as shown in Figure 9.

Change in trading periods from 1 hour to 15 minutes

The TSOs believe that when the market is changed to 15 minutes period of trading energy instead of 60 minutes, the large imbalances between the trading periods (15 minutes instead of 60 minutes) will be lower and will therefore have a stabilizing effect on imbalances and the grid frequency. This is scheduled to happen during the year 2025.

Frequency quality in May

In Figure 15 the frequency has a high-quality during periods of low levels of inertia during the year except for the month of May where we can see a peak of KPI in *mean monthly minutes outside of frequency band ± 0.1 Hz*. The inertia level relative to the actual load is lower in May compared to June and July which might affect the frequency quality since the load in May is about 10% higher compared to July. Additionally, there are often spring floods in May (in Swedish *vårflod*) that can reduce the availability of a-FRR and m-FRR to bring back the frequency into the frequency interval 50 ± 0.1 Hz.

Fast Frequency Reserve (FFR)

Interviews with Fingrid and SvK revealed that it has been successful to establish the frequency product FFR during periods of low levels of inertia, in order to decrease the dip of the grid frequency if large plants or other N-1 events happen. FFR responds very quickly to steep under-frequency changes and compensates for the lost power in the grid. On average, FFR is bought for about 100 hours effectively during a full year which is about 1% of the full year.

FFR does not affect the time outside of 50 ± 0.1 Hz but instead it improves the under-frequency nadir during the event (the lowest frequency value). Therefore, the number of *minutes outside of frequency band ± 0.1 Hz* is not affected by FFR but by other frequency services such as a-FRR and m-FRR.

Inherent capacities to stabilize the grid frequency

One important inherent characteristic of the power system is that the active power is reduced in a load center if the voltage is reduced. This is possible since part of the load has a constant impedance character or constant current character. The importance of this effect was seen for instance during the Hagby event on April 26, 2023, i.e., when the active power of the loads in the Stockholm area close to Hagby were reduced because of their voltage dependence. Forsmark 1 and 2 were disconnected from the grid during the short-circuit that took place during seven seconds in the substation of Hagby. The sub-sequent reduction of the load in the Stockholm area after the short-circuit helped the system to survive and avoided a larger impact from the event. Some loads were even disconnected due to the low voltage levels for an extended time.

Loads in a power system has historically also been frequency-dependent which have had a positive stabilizing effect. During events with low frequency, loads have been reduced, while in case of high frequencies, loads have been increased, which also have had a stabilizing effect on the system. Despite that today (2025) there exist lot of loads including power electronics which makes the load frequency-independent, it is believed that still, parts of the load is frequency-dependent.

5 Conclusion and future outlook

In this report the following have been investigated:

- Historical trends of frequency deviations in the Nordic Power System during the years 2003 – 2023 and future trends that can be seen today.
- Investigation of inertia dependency of nuclear power plants over time as well as different system services in frequency control (primary control) of the Nordic Power System mostly during the years 2016 – 2023.
- Frequency deviations impact on life expectancy of components in nuclear power plants.
- Analysis of current and future trends in frequency quality and system services in the Nordic Power System.

5.1 SHORT CONCLUSIONS

The conclusions in this sub-chapter are a shorter version of the conclusions in Chapter 5.2.

The frequency quality has been investigated in this report for the last two decades (2003 – 2023). The KPI – *minutes outside of frequency band* ± 0.1 Hz has increased during 2005 – 2011 to high values which was caused by HVDC-links that were allowed to do large planned changes in transmitted power and direction. In the second decade these HVDC-links have had regulations on how large the planned changes could be, which has led to a better frequency quality.

The improvement in the KPI during recent years can be a result of the introduction of Automatic Frequency Restoration Reserve (a-FRR) in the year 2013. The volumes of a-FRR has since then increased which can be one reason behind the improvement of the KPI during the last years.

There are however rather long periods of over frequency which are consequences of erroneous forecasts in power production, lot of wind power production, low loads, and a lack of down regulating power as a-FRR down and m-FRR down.

No connection between low levels of inertia and low frequency quality can be found (in the sense of the KPI – *minutes outside of frequency range* ± 0.1 Hz). Instead, it is found that during summer months when the inertia is often very low in the system, the frequency is better than during the other parts of the year. May is the month that has the worse frequency quality, the inertia level is in that month as low as in June and July. An explanation to the low frequency quality can be the spring flood (in Swedish vårflood) that cancels volumes of a-FRR and m-FRR that is needed to control the frequency. Another explanation can be that the load is higher in May compared to June and July so that the amount of inertia in May relatively the load is smaller compared to the situation in June and July. In spite of this it is important to understand that inertia is an important system quantity in case of larger transient events like for instance sudden disconnections of large production units when system inertia supports the power system so that the frequency

deviation becomes smaller. During such periods of low amounts of system inertia, the Nordic TSOs are compensating this by buying Fast Frequency Reserve (FFR) since year 2020.

There are very few events when frequency exceeds 50.3 Hz. The frequency has been higher than 50.3 Hz only for about 2 minutes and 40 seconds during the last 21 years. The frequency has been below 49.7 Hz for about 38 minutes during the last 21 years.

Due to large HVDC interconnectors (1400 MW) connected in the system recently and tripping more often in combination with sudden losses of nuclear production; minimum and maximum peak deviations have becoming higher during the last four years. More often, during export with the HVDC interconnectors, the trips of them today lead to frequencies higher than 50.4 Hz, but this is still well within the level of 51.0 Hz which is the highest allowed frequency (Unlimited in time) in the Requirement RfG [6].⁵ In the large disturbances that led to over-frequencies during 2022 we could see that the amount of inertia has a correlation with the size of the sub-sequent frequency peak.

Statistically it is shown in this report that the frequency is often outside the interval ± 0.1 Hz around the hour shift. There are frequencies very often over 50.1 Hz (6:00, 7:00, and 8:00 EET/Helsinki Time) just before the full hour, while under frequency events happen more often just after the full hour. Some of the reasons influencing this behavior might be differences in fast rate of change of generating units in comparison with slow loads, as well as behavior of generating units due to market signals and difficulties in forecasting some of the units. We foresee changes in the behavior of market participants once the market changes from 1 hour to 15 minutes settlement period, as planned during 2025 which we believe will improve this situation.

Although the annual peak levels of inertia coming from nuclear power plants decreased during the period (2016 – 2023), it can be observed that with the introduction of the new unit Olkiluoto 3 in year 2023 the annual peak of nuclear inertia is back to almost the same level as before Oskarshamn 1, Ringhals 1, and Ringhals 2 were de-commissioned from year 2016.

In addition, we observe that the year 2020 had in general the lowest nuclear inertia of the last decade with a long period of low inertia during summer. However, if we look at frequency quality presented in the report it can be seen that the frequency quality level in 2020 is actually one of the best for the last decade.

The amount of nuclear inertia seems not to decrease further in the coming decades since at the moment (year 2025) several of the nuclear owners in the Nordic countries are examining further lifetime extensions of the existing plants. Also, there are plans of building new NPPs in Sweden in the coming decades so the nuclear inertia can have passed its minimum in the 21st century during 2020 – 2022.

⁵ Only a few large power plants fulfill the RfG [6]. Most of the existing plants are built fulfilling earlier requirements.

In general, the NPP operators do not report any experience with wear and tear caused by grid frequency deviations. Nevertheless, they are interested in learning if there might be any wear and tear issues caused by grid frequency deviations.

More concern is raised from the NPP operators around grid voltage disturbances impact on wear and tear of equipment, which might be of interest for future work.

To conclude, analysis presented shows that frequency levels have peaked above 50.4 Hz only six times during the last two decades indicating that the situation is still far away from critical levels of 51.0 Hz which is the highest allowed frequency (Unlimited in time) in the Requirement RfG [6].

We cannot see any connection between high amounts of wind power and low frequency quality since during the months of high wind power production the grid frequency shows a better frequency quality compared to the months with less wind power production.

The high peaks in frequency is a fairly new phenomenon in the Nordic Power System. It will remain since the cause is the large HVDC-links built 2020 and 2022.

The Nordic TSOs prepares for the worse case which is small amount of inertia. Therefore the TSOs plan to continue to develop the product FFR since it has shown to be a good tool to compensate for the low levels of inertia.

The Nordic TSOs would also like to see larger volumes of regulating power, a-FRR and m-FRR that sometimes are lacking in the control of the power system leading to long durations of over- or under-frequencies.

5.2 EXTENDED CONCLUSIONS

5.2.1 Frequency quality

We can conclude; frequency quality has been getting better over the course of the last four years when we observe average daily frequency in period between 2003 and 2023. It remains within the limits of ± 0.1 Hz through all the years and there is a trend of average value being closer to 50.0 Hz in the last four years. This, together with increased frequency quality in terms of KPI – *Minutes outside of frequency range ± 0.1 Hz*, implies that the frequency quality is improving in the Nordic Power System in the last four years.

Between 2005 – 2011 the numbers of HVDC interconnectors were increasing and their operation was not regulated which led to large abrupt changes of power which often worsened the frequency in the Nordic Power System. After 2011, the TSOs introduced new rules on how to operate HVDC interconnectors which led to improved frequency quality.

During twenty-one years, the frequency has been higher than 50.1 Hz at 7:00 in the morning (EET/Helsinki Time) at 300 days which is a clear signal that the frequency quality is worse during large load changes in the morning around the full hours.

One explanation why a correlation between low levels of inertia and frequency quality is not clear, is the introduction of system services that counteract the lower

levels of inertia, such as FFR. Also, the normal operations of HVDC-links nowadays is limited in how they can be operated which leads to improvement of the frequency quality.

5.2.2 Inertia and frequency quality

The inertia of the Nordic Power System has been examined for the last eight years (2016 – 2023).

We observe the seasonal nature of inertia where inertia levels are lower in the summer and higher in the winter. Average lower levels of inertia rarely go below 125 GWs and are kept to that season-low level mostly constant during the last eight years. But, a slight decreasing trend of average daily winter inertia values (the higher seasonal levels) can be observed during the last eight years of available data, with a slight increase in the winter of 2023.

It can be observed how the revisions in the nuclear plants every year reduce the available nuclear inertia from about May – September. The low levels of inertia from nuclear goes down to almost the same levels for all summers over the last eight years, around 35 – 45 GWs, even though the total number of NPP has been reduced with three plants during the same period.

The trend of decreasing value in total inertia can in one part be connected with the process of decommissioning of nuclear power plants in the Nordic Power System.

Although the annual peak levels of inertia coming from nuclear power plants decreased during the period (2016 – 2023), it can be observed that, with the introduction of the new unit Olkiluoto 3 in year 2023, the annual peak of nuclear inertia is back to almost the same level as before Oskarshamn 1, Ringhals 1, and Ringhals 2 were decommissioned from year 2016.

In addition, we observe that the year 2020 had in general the lowest nuclear inertia of the last decade with a long period of low inertia during summer. However, if we look at frequency quality presented in the report it can be seen that the frequency quality level in 2020 is actually one of the best for the last decade.

We observe high frequency quality during periods of low levels of inertia during June to October except for the month of May where we can see a peak of KPI in *mean monthly minutes outside of frequency band ± 0.1 Hz*. The inertia level relative to the actual load is lower in May compared to June and July which might affect the frequency quality. The load in May is about 10% higher compared to July. Also, in May it is often spring flood (in Swedish *vårflod*) that can reduce available a-FRR and m-FRR leading to an insufficient situation to bring back the frequency into the frequency interval 50 ± 0.1 Hz.

Therefore, we cannot bring any clear correlation between frequency quality and inertia in general nor nuclear inertia (in the sense of the KPI – *minutes outside of frequency range ± 0.1 Hz*). We observe that during summer months, when inertia is often very low in the system, frequency quality is better than during other months of the year.

In spite of this it is important to understand that inertia is an important system quantity in case of larger transient events like for instance sudden disconnections of large production units when system inertia supports the power system so that the sub-sequent frequency deviation becomes smaller.

The amount of nuclear inertia seems not to decrease further in the coming decades since at the moment (year 2025) several of the nuclear owners in the Nordic countries are examining lifetime extensions of the existing plants. Also, there are plans of building new NPPs in Sweden in the coming decades so the nuclear inertia can have passed its minimum in the 21st century during 2020 – 2022.

5.2.3 Wear and tear of components influenced by grid frequency variations

In general, the NPP operators do not report any experience with wear and tear caused by grid frequency deviations. Nevertheless, they are interested in learning if there might be any wear and tear issues caused by grid frequency deviations.

Regarding NPP tripping, there are differences between the plants in the number of disturbances, as well as recent trends. During the last two decades, some NPP operators report seldom trips, while others report trends of tripping happening more often. If those trips are caused by grid faults, this is usually due to disturbances in the voltage and not in the frequency.

Therefore, more concern is raised about grid voltage disturbances impact on wear and tear of equipment, which might be of interest for future work. For example, voltage variations in a grid close to one of the NPPs is compensated for by the control of the main NPP generator. This control is always active and implies variations of the field current in the rotor. Such variations cause extra thermal wear and tear except for the normal wear and tear associated to the active power production.

For the future outlook, some NPP operators report concern that the increased complexity of the power system will imply more frequent blackouts, and such events will include frequency or voltage deviations which may be outside of the current grid requirements. In addition, NPP operators are concerned about the increased amount of inverter connected production and are interested in whether it can create problems in the existing power plants production environment.

To conclude, analysis presented shows that frequency levels have peaked above 50.4 Hz only six times during the last two decades indicating that the situation is still far away from critical levels of 51.0 Hz.

We can also see that the frequency has been higher than 50.3 Hz only for a total of about 2 minutes and 40 seconds during the last twenty-one years, which is a rather short time.

5.2.4 Current and future trends in system services in the Nordic Power System

The HVDC-links connected to the Nordic countries today have regulations that are limiting their normal operation concerning the size of changes in transmitted power in order to not introduce large events of imbalances and frequency changes.

However, in the case of a large HVDC trip, i.e., 1400 MW, this creates a large system event. Since HVDC links are exporting the majority of the time, this often leads to very high over-frequencies in the Nordic Power System that has been seen during the last four years. These high frequency peaks are a new characteristic of the Nordic Power System.

The peaks are, however, still below the RfG requirements [6] which allows frequencies of up to 51.0 Hz (Unlimited time). It is believed that these high peaks in frequency will also be present in the future because of these recently established large HVDC links.

Frequency services for over-frequencies such as FFR or future Dynamic FFR are believed to be able to counteract large frequency deviations related to large events, however FFR is not activated as of today (2025) for over-frequencies. It can therefore be beneficial to develop such frequency products also for over-frequencies in periods of low inertia.

Considering the number of short frequency dips, these are to a majority caused by nuclear power plant trips and recent trips of importing HVDC-links. There are also however other grid events causing these frequency dips. These dips have been present during the last decades and will continue to be a part of the system. The system service that is used to reduce the magnitude of these dips in frequency is FFR and it has been shown that FFR is a rather effective solution to support the system in conditions with low levels of inertia when large production units or importing HVDC links trip.

Several events with long duration when the frequency is higher than 50.1 Hz have been presented. Also, it is shown that these events happen often during the night and around the full hour. The longest interval in which frequency was constantly above 50.1 Hz lasted around 38 minutes.

Frequency is often high in the morning hours. One reason for this is that during these events the amount of down regulating capacity in m-FRR is not sufficient. Circumstances that are impacting these frequency conditions include very windy conditions, low prices, erroneously forecasting, high import of power from Continental Europe, and low load. At such circumstances the controllable power such as hydropower and thermal power is producing less because of the low electricity price which leads to a lack of m-FRR. This is a consequence of that it is mostly hydropower and thermal power that deliver m-FRR. Therefore, it is of importance to expand the volumes of m-FRR in the future to include other types of production, for instance wind power.

It has been shown that the number and the periods of low frequencies are about constant during the last two decades, i.e., the production mix is changing but new frequency services have been applied to the Nordic Power System and these services have been effective to keep the amounts of low frequencies and their durations at the same level as before. During the last four years (2020-2023) the number of events with low frequencies and their duration has even been reduced. Products like a-FRR up and m-FRR up have improved the frequency quality and today we can see fewer long durations of low frequencies.

The TSOs believe that when the market is changed to 15 minutes period of settlement of energy instead of 60 minutes, the large imbalances between the trading periods will be lower and will therefore have a stabilizing effect on imbalances and the grid frequency. This is scheduled to happen during the year 2025.

Interviews with Fingrid and SvK revealed that it has been successful to establish the frequency product FFR during periods of low levels of inertia, in order to decrease the dip of the grid frequency if large plants or other N-1 events happen. FFR responds very quickly to steep frequency changes and compensates for the lost power in the grid. On average, FFR is bought for about 100 hours effectively during a full year. FFR does not affect the time outside of 50 ± 0.1 Hz but instead it improves the frequency nadir during the event. So, the number of *minutes outside of frequency band ± 0.1 Hz* is affected by other frequency services such as a-FRR and m-FRR.

One important inherent characteristic of the power system is that the active power is reduced in a load center if the voltage is reduced. This is possible since the load has a constant impedance character and/or a constant current character. The importance of this effect was seen during the Hagby event on April 26, 2023, when the active power of the loads in the Stockholm area close to Hagby were reduced because of their voltage dependence at the same time that Forsmark 1 and 2 were disconnected from the grid during the short-circuit that happened in the substation of Hagby. The reduction of the load in the Stockholm area helped the system to survive and avoided a larger impact from the event.

Loads in a power system also depend on the grid frequency which also has a positive stabilizing effect. During events with low frequency, loads are reduced, while in case of high frequencies, loads are increasing, which has a stabilizing effect on the system.

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TRENDS OF FREQUENCY DEVIATIONS

In this report grid frequency statistics of the last two decades have been examined together with analysis of inertia values of the Nordic Power System. Interviews have been held with the Nordic Nuclear Production Plant owners and the Swedish and Finnish TSOs. Conclusions are made whether it exist correlations with system quantities like frequency quality, inertia, wind power production, wear and tear of nuclear plants, and system services.

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