European Network of
Transmission System Operators
for Electricity

Overview of Frequency Control in the Nordic Power System

Nordic Analysis Group

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Contents

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List of Abbreviations

ACE	Area Control Error
AOF	Activation Optimization Function
aFRR	Automatic Frequency Restoration Reserve
BRP	Balance Responsible Party
BSP	Balancing Service Provider
DCC	Demand Connection Code
EBGL	Guideline on electricity balancing
ENTSO-E	European Network of Transmission System Operators for Electricity
EPC	Emergency Power Control
FCR-N	Frequency Containment Reserve – Normal operation
FCR-D	Frequency Containment Reserve – Disturbance
FFR	Fast Frequency Reserve
FRCE	Frequency Restoration Control Error
FSM	Frequency Sensitive Mode
HVDC	High Voltage Direct Current or Requirements for Grid Connection of High Voltage Direct Current Systems
ISP	Imbalance Settlement Period
LER	Limited Energy Reservoir
LFC	Load Frequency Control
LFDD	Low Frequency Demand Disconnection
LFSM	Limited Frequency Sensitive Mode
LFSM-O	Limited Frequency Sensitive Mode – Over-frequency
LFSM-U	Limited Frequency Sensitive Mode – Under-frequency
mFRR	Manual Frequency Restoration Reserve
mHz	Millihertz
NC ER	Network Code for Emergency and Restoration
RfG	Requirements for grid connection of Generators
SCADA	Supervisory Control And Data Acquisition
SOA	Nordic System Operation Agreement
SOGL	Guideline on electricity transmission system operation
TSO	Transmission System Operator

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1. Introduction

To securely operate a power system several attributes need to be controlled, one of these is the frequency. The purpose of this report is to give an overview to the frequency control in the Nordic power system. The report is mainly focused on the technical aspects related to frequency stability.

The frequency is the number of periods per second in an alternating voltage power system and is measured in Hertz (Hz). To achieve good power quality and stability it is important for the Transmission System Operators (TSOs) within a power system to limit the frequency deviations. If the frequency deviation is too large, power generating units cannot continue to operate and will be disconnected from the grid.

The Nordic power system is designed for a nominal frequency of 50 Hz, however, the actual frequency always fluctuates around the nominal value depending on the imbalance between production and consumption. When there is more electricity production than consumption the frequency will start to increase and vice versa. The system kinetic energy (inertia) resists the frequency change. The Nordic power system is dominated by synchronous generators which have a rotor and its rotation generates the alternating voltage, the rotational speed of the rotor defines the frequency. The kinetic energy in the system comes from the synchronously connected rotational masses that include generators and turbines.

Power system frequency mainly depends on three factors:

- Power imbalance is the power difference between production and consumption. The imbalance is the driving force for the frequency change. A larger imbalance will generate a larger frequency deviation. A large imbalance can be caused by a disconnection of a large production unit or an interconnector to another synchronous area. Smaller imbalances are normally caused by stochastic changes in the consumption and production. The worst single disturbance that can occur in the power system is defined as the reference incident.
- Kinetic energy is the stored rotational energy in all synchronously connected machines. The higher the kinetic energy in the power system, the harder it is to change the frequency. When the frequency starts to change, the masses in the synchronously connected machines start to absorb or deliver electric power from the rotational energy. With a higher kinetic energy there is more rotating mass to mitigate the change in frequency the power imbalance is causing.
- Reserves from power generating units, consumption units and energy storage units that control their power exchange with the grid in order to keep the power system in balance. There are several types of reserves for different purposes: from very fast automatic frequency control to slower manually activated balancing reserves.

On a higher level the frequency control can be described through two processes: the frequency containment process and the frequency restoration process. The frequency containment reserves are the first reserves to react to imbalances. They stabilize the frequency, and their activation is directly based on measured frequency deviation. The frequency restoration reserves are used to restore the frequency back to 50 Hz and to release the activated frequency containment reserves, so that they are ready to activate again when needed.

The frequency control reserves in the Nordic power system can be divided into three subgroups:

- Frequency Containment Reserves (FCR)
  The objective of FCR is to stabilise and maintain the frequency in case of imbalances. FCR is a fast power activation that activates automatically and proportionally in response to a deviation in frequency within certain intervals. FCR for normal operation (FCR-N) stabilises fluctuations between production and consumption in normal operation and FCR for disturbances (FCR-D) stabilises large power imbalances that may occur.
- Frequency Restoration Reserves (FRR)
  FRR restores the frequency to 50 Hz after a deviation, thereby relieving FCR and restoring FCR

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capacity since the frequency deviation will go to zero. To do this, the FRR is activated based on the integrated frequency deviation. FRR is not as fast as FCR. FRR is divided into two parts, automatic FRR and manual FRR.

- Fast Frequency Reserve (FFR)
  FFR provides very fast power response after activation. The reserve is utilized in situations with low levels of kinetic energy in the power system in combination with a risk of high imbalance. In such situations the FCR response might not be sufficient to stabilise and keep the frequency within limits on its own. The FFR is a very fast step wise power activation when the frequency passes the activation threshold.

In addition to the market based products, several measures for emergency and restoration state exist, as introduced in chapter 5.

To ensure secure operation the TSOs must ensure availability of sufficient frequency reserves to avoid disconnection of either production or consumption. If units start to disconnect due to high frequency deviation, there is a high risk that the situation escalates to a blackout of parts of or the entire system.

Figure 1 shows an example of a frequency disturbance and the corresponding activations for the different frequency reserves. FCR-N is not included in the figure since a larger disturbance is illustrated.

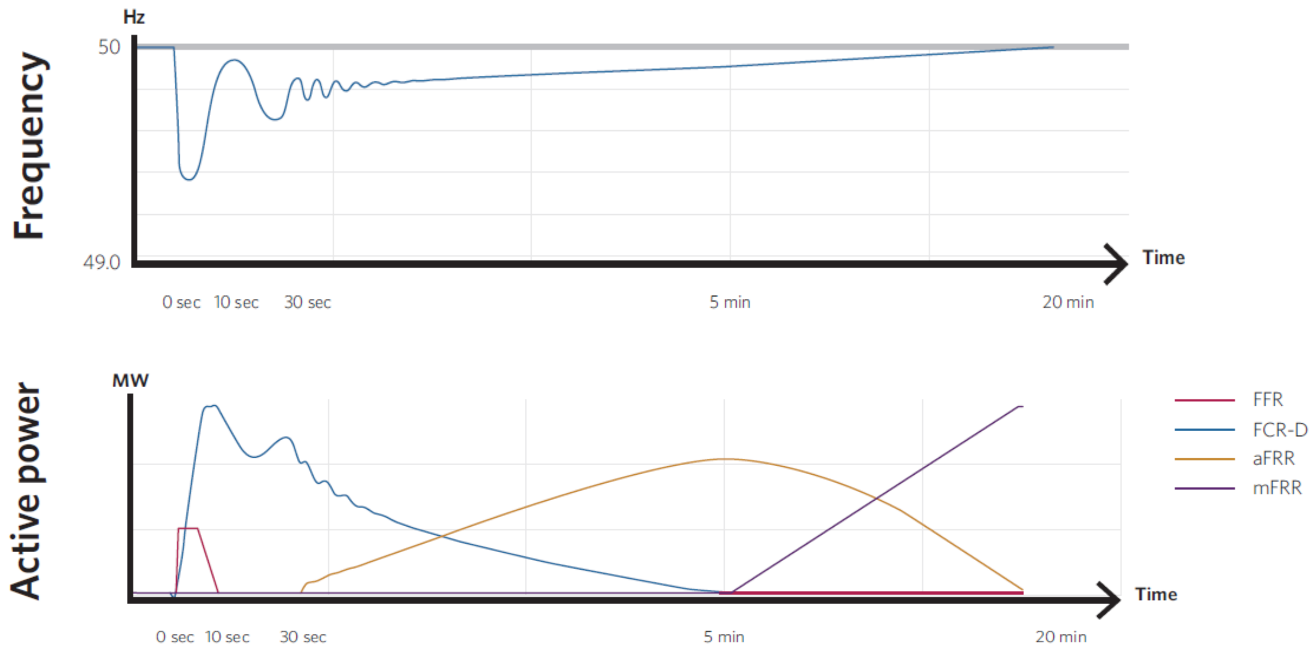

Figure 1: Example of a frequency disturbance and illustration of the different reserve activations.

1.1 Guiding documents

European legislation on electricity transmission system operation, the SOGL [1], sets guidelines on topics related to load-frequency control. These include for example dimensioning of reserves, exchange and sharing of reserves between TSOs, minimum technical requirements and frequency quality targets. European legislation on electricity balancing, the EBGL [2], covers topics related to procurement of reserves and minimum requirements to reserve products. The Nordic System Operation Agreement – Annex Load-Frequency Control & Reserves [3] further elaborates the requirements of SOGL and EBGL in a Nordic context to ensure that the Nordic synchronous area is operated on a high level of reliability and quality. The connection network codes NC RfG [4], NC DCC [5] and NC HVDC [6] sets requirements on capabilities from new or revised equipment, including related to frequency control. The network code on Emergency and Restoration (NC ER) [7] supplements SO GL with requirements related to large incidents and the corresponding system states.

1.2 System states

The power system is considered to be in different states depending on the actual frequency, frequency deviation in case of a disturbance, controllability and observability of the frequency. There are five different system states: Normal, Alert, Emergency, Blackout and Restoration [1]. The first three of them are illustrated in Figure 2 with respect to frequency.

Figure 2: System state limits with respect to frequency in the Nordic power system. Normal state is shown in green, Alert state in yellow and Emergency state in red.

In the Nordic power system the standard frequency range is 50 Hz ±100 mHz. During large imbalance events the frequency is allowed to transiently deviate ±1000 mHz for up to 60 seconds, after which the frequency has to settle within ±500 mHz. The target for frequency quality is to only allow the frequency to deviate outside the standard frequency range for maximum 15 000 minutes per year, as stated in SOGL [1]. The Nordic TSOs aim to keep the frequency from deviating outside the standard frequency range to 10 000 minutes per year. The technical requirements and procurement of FRR, FCR and FFR aims to ensure that the power system remains in the normal state for the worst disturbance of a single unit, the so-called reference incident. 15 minutes after a disturbance the reserves shall be restored and ready to handle a new reference incident again.

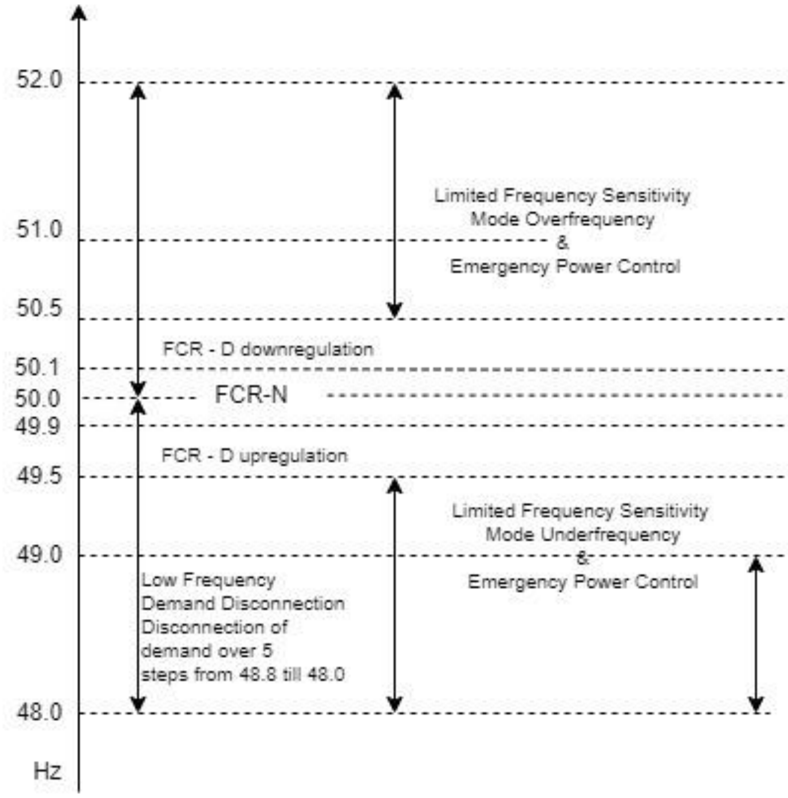

Figure 3 shows the different measures taken at different frequency thresholds.

The TSOs have designed different kinds of remedial actions or system services for each of the different system states. If the power system at any time risks to deviate from normal state according to Figure 2, the TSOs needs to initiate remedial actions to get the power system state back to normal. Figure 3 shows the different measures taken at different frequency thresholds. The aim for these actions is either to keep the system in normal state, get the system back to normal state when deviating or to minimize the consequence of a deviation from the normal state. Remedial actions for Emergency and Restoration states are further described in Section 5.

1.3 Performance and stability of the frequency control

When describing the frequency control there are two important aspects: performance and stability. Performance is the ability to react to a large disturbance and still keep the frequency within acceptable limits. This describes the speed of the reserve activation. Stability is the ability to supply sufficient damping when the frequency is oscillating.

Both aspects are important and might come as a trade-off. If a provider increases the performance (speed of the response) of their reserve providing unit, there is a risk the unit will reduce the stability margin or even become unstable and increase frequency oscillations in the system. Figure 4 shows a frequency disturbance where the performance explains the ability to keep the initial frequency swing within the limits. Stability explains the ability to dampen the oscillations in frequency following the first swing. The magnitude of every arrow in the figure is reducing with time, indicating positive damping.

It is important to ensure both the performance and stability of the frequency control to ensure the power system to operate in normal state.

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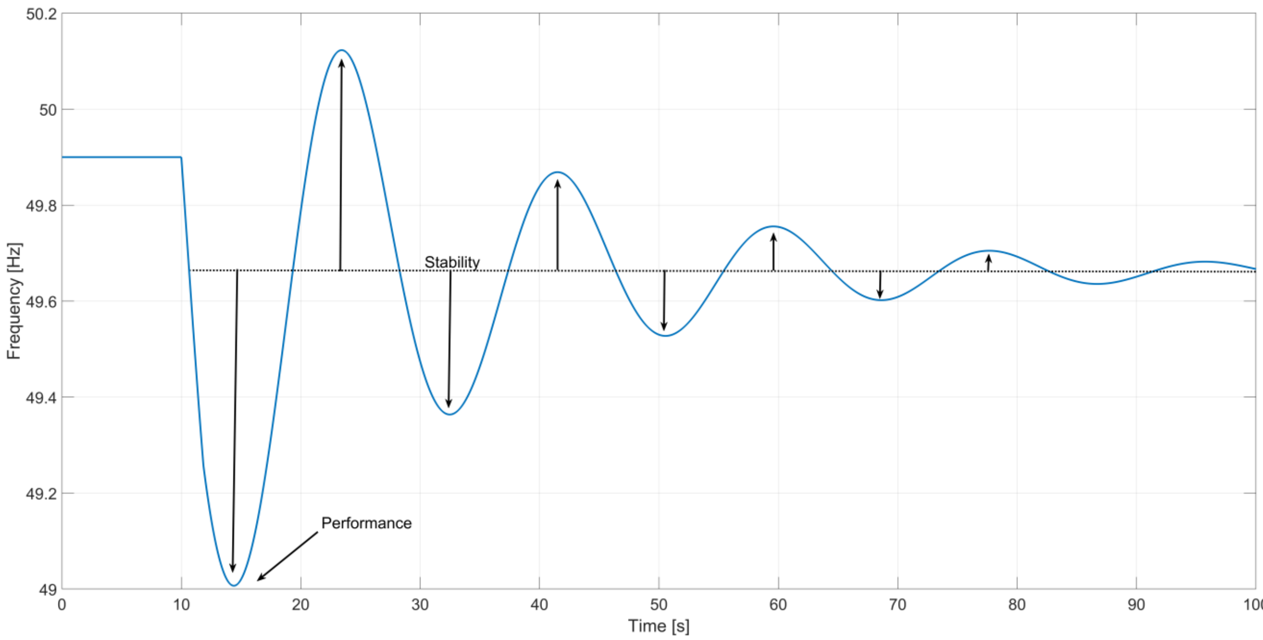

Figure 4: Frequency disturbance illustrating the aspect of performance as the ability to limit the frequency deviation for the initial swing and the stability as the ability to dampen the following frequency oscillations.

1.4 Electricity markets and balancing responsibility

Electricity is sold and procured at markets and the balance responsible parties (BRP) are obligated to maintain their balances on a trading period basis, according to the rules for BRPs. A smaller portion of the trade is made bilaterally directly between two traders.

The electricity market is an energy market where energy imbalances are considered during each trading period. The BRPs have to forecast production and consumption for the trading periods and the total error affects the total imbalance. The BRPs are financially responsible for their imbalances.

The term imbalance can have different meanings. Imbalance can for example mean the momentary imbalance between production and consumption at a given moment. Momentary imbalances may occur due to sudden disconnection of generation or load, but they also occur due to natural variations in production and consumption. Imbalance can also mean the difference between real-time measured and traded power.

The most energy volumes are traded in either the day-ahead or the intraday markets. The day-ahead market is a market place for trading electricity for delivery the next day ($D-1$). Market participants submit their bids for production or consumption in the respective bidding zone before gate closure, which is at 12:00 CET the day before operation. The bids are processed, the price equilibrium for the system is calculated and the outcome is released at 12.45 CET. If there are congestions between bidding zones, the price will differentiate between different zones. The intraday market provides a possibility for BRPs to trade themselves into balance closer to the start of the trading period. After gate closure, the transmission system operators (TSOs) are responsible for balancing the system in real time. Currently the trading periods are one hour but this will in the near future change to 15 minutes.

2. Frequency control products

At present there are five frequency control products in use in the Nordic power system. A short description of each product is given below.

In addition to the market based products, several measures for emergency and restoration state exist, as introduced in chapter 5.

2.1 Frequency Containment Reserve – Normal (FCR-N)

The Frequency Containment Reserve for Normal Operation (FCR-N) is linearly activated within the standard frequency range 49.9 –50.1 Hz. It activates continuously as the frequency fluctuates around 50.0 Hz due to small variations in production and consumption that occur during normal operation. FCR-N is a symmetrical product, which means that the FCR providing entity has to be able to both decrease and increase its power production or consumption depending on the direction of the frequency deviation. FCR-N must activate approximately 63% within 60 seconds and 95% within 3 minutes.

2.2 Frequency Containment Reserve – Disturbance (FCR-D)

The purpose of the Frequency Containment Reserve for Disturbances (FCR-D) is to contain frequency during disturbances. Separate products exist for upregulation i.e. for underfrequency disturbances (loss of production or HVDC-import from another synchronous area) and for downregulation i.e. for overfrequency disturbances (loss of consumption or HVDC-export to another synchronous area). The FCR-D upwards and downwards products are linearly activated between 49.5 –49.9 Hz and 50.1-50.5 Hz, respectively. 86% of the active power must be activated within 7.5 seconds and the activated energy after 7.5 seconds must be 3.2 seconds times the steady state power of the FCR-D delivery.

FCR-D providing entities without the capability to provide a continuous and dynamic response has the ability to prequalify for a special version of FCR_D denoted as “Static”. A certain amount of the total FCR-D response will have to come from reserves with dynamic capabilities, and hence the Nordic TSOs is currently investigating how to implement a quota to limit the amount of Static FCR-D to an acceptable level.

2.3 Fast Frequency Reserve (FFR)

The Fast Frequency Reserve (FFR) was implemented in the Nordics in 2020. In today’s power system the kinetic energy (inertia) is at times so low that the activation of FCR-D is not fast enough to guarantee frequency stability during a large disturbance. FFR was introduced to handle this problem. It provides a very fast power response for a short duration, which contributes to containing the frequency until FCR-D is activated. Similar to FCR-D, FFR is currently only an upregulation product. FFR is triggered when the frequency crosses the activation threshold. The activation threshold is at 49.5 Hz, 49.6 Hz or 49.7Hz. The full activation time is 0.7–1.3 seconds depending on the activation threshold. The minimum support duration is either 30 seconds or 5 seconds, depending on how fast the FFR providing unit deactivates its response.

The current FFR is a static product, meaning that it does not continuously follow frequency variations but rather follows a fixed profile after a specified threshold has been reached. The Nordic TSOs are investigating the possibility to include a Dynamic variation of FFR, similarly to FCR-D which exists I a Dynamic and Static version respectively.

Limiting the size of the reference incident

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If the current reference incident is larger than the power system can handle without deviating from normal state, the TSOs can limit the power in order to be able to handle the disturbance. The TSOs will then limit the reference incident to a level the power system can withstand and still be in normal state. This is the measure that was utilised in low inertia periods prior to implementation of FFR and it is still an option if needed. However, procurement of FFR is the preferred option.

2.4 Automatic Frequency Restoration Reserve (aFRR)

The Automatic Frequency Restoration Reserve is used to restore the frequency back to its nominal value of 50 Hz. aFRR is used for both up- and downregulation. The activation of an aFRR providing unit is based on a control signal sent every 10 s by the connecting TSO. The aFRR is activated continuously. The maximum allowed full activation time for an aFRR unit is 5 minutes.

2.5 Manual Frequency Restoration Reserve (mFRR)

The Manual Frequency Restoration Reserve serves the same purpose as aFRR: to restore the frequency back to 50 Hz. mFRR is used for both up- and downregulation. The full activation time is 15 minutes. mFRR is the only manual reserve product used in the Nordics. Activations are ordered by the TSO and can be done to reduce existing imbalances or because of forecasted imbalances in the near future. The mFRR markets consists of the Nordic energy activation market (mFRR EAM) and national mFRR capacity markets (mFRR CM).

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3. Dimensioning of reserves in the Nordic power system

The Nordic TSOs dimension the different reserves together. The dimensioning defines the needed amount of reserves in the system and their distribution between the individual TSOs. This chapter explains the dimensioning principles of each reserve.

3.1 Frequency Containment Reserve – Normal (FCR-N)

The Nordic TSOs divide FCR in two types of products, FCR-N and FCR-D, whereas the SOGL dimensioning requirements mainly focus on FCR for disturbance events, which corresponds to the Nordic's FCR-D. FCR-D is explained separately in Section 3.2.

Currently the volume of FCR-N is based on historic assumptions of random load variation of ± 1 % of 60 GW. The Nordic area currently secures 600 MW symmetric FCR-N capacity throughout the year.

The distribution of the required volume between the TSOs (in the same LFC block) is based on the principle stated in SOGL: "the shares of the reserve capacity on FCR required for each TSO as initial FCR obligation shall be based on the sum of the net generation and consumption of its control area divided by the sum of net generation and consumption of the synchronous area over a period of 1 year".

The equation of the FCR share of TSO 1 is then

$$FCRshare_{TSO\ 1} = \frac{Generation_{TSO\ 1} + Consumption_{TSO\ 1}}{\sum_{i=1}^{4}(Generation_{TSO\ i} + Consumption_{TSO\ i})} \qquad \text{(eq. 1)}$$

Each year the individual shares have to be revised on the basis of previous annual consumption and generation. The share is rounded to the closest integer given in MW. The same sharing key is applied to both FCR-N and FCR-D. Table 1 shows the shares per TSO for 2024.

Table 1: FCR shares for the year 2024

TSO	Share [%]
Energinet (DK2)	2.97
Fingrid	20.29
Statnett	37.61
Svenska kraftnät	39.10

3.2 Frequency Containment Reserve – Disturbance (FCR-D)

The dimensioning principle for FCR-D is defined in SOGL [1] that states that the reserve capacity for FCR-D shall at least cover the reference incident in the upward and downward directions respectively. The downward direction is here defined as a power surplus and the upward direction as a power shortage in the power system.

The following reference incidents are considered in the FCR-D dimensioning process:

- Single power generating module – e.g. tripping of Oskarshamn 3 in Sweden.
- Single demand facility – e.g. tripping of a aluminum smelter hall in Norway.
- Single HVDC interconnector – e.g. tripping of NordLink in import/export situation.

- Tripping of an AC-line – e.g. tripping of lines(s) Hasle-Halden resulting in system protection scheme (SPS) activation in Norway.
- Single failure on a busbar tripping more than one generation module or demand facility.

3.3 Fast Frequency Reserve (FFR)

The amount of kinetic energy in the Nordic power system determines the required amount of FFR capacity to keep the frequency minimum above 49.0 Hz in case of a loss of the reference incident. This amount is dynamic over the hours of a day and over seasons, due to the constant change of kinetic energy. The needed total FFR capacity is calculated by using a short-term forecast of the kinetic energy and by simulating the loss of the valid reference incident at the target day. The total capacity is distributed between the TSOs.

Table 2 shows the shares per TSO in percent and in MW based on an assumption of 300 MW of FFR on Nordic level.

The TSOs have chosen different procurement strategies to fulfill their share.

Table 2: FFR shares for the year 2024

TSO	Share [%]	Share [MW]
Energinet	8	24
Fingrid	18	54
Statnett	39	117
Svenska kraftnät	35	105

The shares are updated annually.

3.4 Automatic Frequency Restoration Reserve (aFRR)

The dimensioning of aFRR is currently based on the targeted frequency quality. At present, the aFRR procurement is focused on hours where it is most challenging to maintain good frequency quality. In the past years the morning and the evening hours have been the most challenging, because during those times of the day the imbalances between electricity production and consumption are substantial. However, imbalances are in general increasing and therefore aFRR is now procured for almost every hour of the day and will in the future be procured every hour. When aFRR is procured, the total Nordic minimum volume is 300 MW. The maximum procured volume is currently set to 400 MW. The aFRR volumes and the procurement hours are determined quarterly by the Nordic TSOs together based on assessment of frequency quality. The total volume is distributed between the TSOs as shown in Table 3.

The aFRR volumes are expected to increase as the Nordic Balancing Model (NBM) is implemented (see section 7.1).

Table 3: aFRR shares for the year 2024

TSO	Upregulation share [%]	Downregulation share [%]	Upregulation share [MW] (minimum)	Downregulation share [MW] (minimum)
Energinet	13	13	39	39
Fingrid	15	16	45	48

Statnett	46	43	138	129
Svenska Kraftnät	26	28	78	84

3.5 Manual Frequency Restoration Reserve (mFRR)

The volume of mFRR must be sufficient to cover the reference incident, similar as for FCR-D. Unlike for FCR-D, each TSO dimensions according to their national reference incident and not for the common reference incident in the Nordics. The TSO must distribute the mFRR volume in consideration of local requirements, such as congestions. The mFRR volumes are curently being increased to also consider stochastic imbalances. Stochastic imbalances are imbalances that varies continuously and arise due to deviations from scheduled consumption and production from energy markets, for example forecasting errors of consumption and variable energy sources.

4. Procurement of reserves

Each TSO is responsible for procuring reserves according to their obligations and needs. The procurement of the different reserves for each TSO is briefly explained below. More information about the markets in each country can be found in the national terms and conditions for Balancing Service Providers.

4.1 Frequency Containment Reserve – Normal (FCR-N)

At present there is no common Nordic market, national markets are in place. However, the TSOs can exchange FCR-N, i.e. one TSO can procure capacity from the local market and sell it to another TSO. Each TSO may cover maximum 1/3 of its FCR-N obligation through exchange.

Fingrid

Fingrid procures FCR-N from two national markets: the yearly market and the hourly market. In addition to the national markets and Nordic exchange, Fingrid procures FCR-N from Estonia.

In the yearly market the FCR-N capacity is contracted for a calendar year at a fixed price. A tender is organized every autumn for the next calendar year. The highest accepted bid sets the yearly market price, and all BSPs are renumerated based on the same price (marginal price). BSPs with yearly contracts submit their reserve plan to Fingrid each evening for all hours of the following day. The reserve plan contains the maintained FCR-N capacity and is binding for the BSP. The maintained capacity can be maximum the contracted volume.

Fingrid procures FCR-N capacity from the hourly market daily for the hours of the following day. The procured volume from the hourly market varies depending on the maintained capacity from the yearly contracts and on the amount and price of capacity available from other TSOs. The price on the hourly market is defined for each hour with the marginal pricing principle.

Energinet and Svenska kraftnät

Energinet and Svenska kraftnät procures FCR-N from a common Danish-Swedish hourly market. The markets have two auctions, the first before the closure of the day-ahead market and the second after the clearing of the day-ahead market. The pricing mechanism is marginal pricing.

The sum of the Danish and Swedish obligation is procured each hour as a minimum on the common market. There is no restriction on the exchange of reserves from Sweden to Denmark as long as the available transmission capacity is taken into consideration.

Statnett

Providers offer their capacity to Statnett in markets, which consist currently in a day-ahead and a D-2 market. The price settlement of both markets is marginal pricing, where D-1 price settlement is after clearing of the wholesale energy market. The bids are submitted hourly and per bidding zone.

In case congestions emerge after the day-ahead spot market, Statnett has the option to buy FCR capacity mitigating congestions for a higher market price. These offers are handled with the pay-as-bid principle.

At present Statnett also imposes droop control requirements on all synchronous generation through the connection agreements in order to support potential islanding areas with enough reserve capabilities for frequency control. This is known as base-delivery (grunnleveranse). Exceptions from this requirement can be requested individually. The requirements will be reassessed, considering experiences from the transition to the technical requirements defined in *Technical Requirements for FCR provision in the Nordic Synchronous Area*.

4.2 Frequency Containment Reserve – Disturbance (FCR-D)

As with FCR-N, there is no common Nordic market for FCR-D, but reserves can be exchanged between the TSOs.

Fingrid

Fingrid procures FCR-D from two markets: the yearly market and the hourly market. They work in the same way as the corresponding FCR-N markets.

Energinet and Svenska kraftnät

Energinet and Svenska kraftnät procures FCR-D from a common Danish-Swedish hourly market. It works in the same way as the corresponding common FCR-N market.

Statnett

The FCR-D market follows the same market design as FCR-N.

4.3 Fast Frequency Reserve (FFR)

The procurement of FFR started in 2020, when each TSO implemented a national FFR market. The intention is to in the future also be able to exchange FFR between the TSOs, but solutions for trading have not been implemented yet.

Fingrid

Fingrid procures FFR from an hourly market which is similar to the hourly market in FCR-N and FCR-D. Fingrid procures FFR daily for the next day according to the forecasted FFR need per hour. The pricing principle is marginal pricing. The closure of the FFR market is after the day-ahead market, the day before operation.

To enable more flexible bidding of resources that can deliver either FCR-D or FFR, the BSPs have the option of submitting a combined bid for the two products. If the capacity offered is not procured in the FFR market, it will either be used in the yearly FCR-D market or participate in the FCR-D hourly market auction.

In addition to the national market Fingrid may procure FFR through interconnectors to Estonia.

Svenska kraftnät

Svenska kraftnät procures FFR from a merit order list which is set for the season. The list is static but each bid can be opted out of if the resource is unavailable. Svenska kraftnät procures FFR two times per week, for a 4-day period on Mondays and a 3-day period on Fridays. The procurement is done according to the forecasted FFR need per hour and the pricing principle is marginal pricing.

Energinet

Energinet procures FFR from an hourly market, similar to the Finnish FFR market. The closure of the FFR market is after the day-ahead market, the day before operation. Energinet also procures FFR daily for the next day according to the forecasted FFR need per hour. The pricing principle is marginal pricing.

Statnett

Statnett procures FFR in a seasonal market, where providers can offer FFR for the entire season or just for parts of the season. Therefore, two reserve products are designed. The first product – FFR profil, is a fixed capacity over the season for certain hours, when demand for FFR is expected to be at its highest. Typically, this is during night hours and weekends in the summer. The product FFR flex, is a guaranteed amount of delivery hours, where Statnett can order capacity short-term on request.

The capacity market is settled by marginal pricing and for FFR activation arising costs are reimbursed.

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4.4 Automatic Frequency Restoration Reserve (aFRR)

Currently there is a common Nordic capacity market for aFRR, which all Nordic TSOs are connected to. The capacity market for aFRR is a daily market, where the resolution for the bids is one hour. The market opens at D-7 and closes at D-1 at 07:30 (GCT). The TSOs procure the needed aFRR volume in price order, and the provider is paid according to the most expensive accepted bid (marginal price principle). The TSOs must fulfil their local aFRR need, by either procuring the needed reserves locally, or by reservations transfer capacity in the grid to/from the area where aFRR has been purchased from. This reservation is handled on the Nordic aFRR capacity market.

The aFRR capacity procured on the capacity market is obligated to deliver aFRR energy when needed. The TSOs will in the future join the European PICASSO energy activation market, as further explained in Section 7.1.

4.5 Manual Frequency Restoration Reserve (mFRR)

Common Nordic energy activation market

The mFRR energy bids for each country are combined in the common Nordic energy activation market. The market opens 14 days before the hour of operation, with a gate closure time 45 minutes before the relevant operational hour. BSPs can submit and change their bids up until the gate closure. Bids are then activated by the TSO during real time based on the system needs, in accordance with the common Nordic merit order list based on the pricing. The balancing energy price is determined after the end of the operational hour based on marginal pricing. If congestions arise, there can be different prices in the different bidding zones. Bids are submitted separately for upward and downward regulation.

Currently each TSO has national mechanisms to secure mFRR capacity. In the future there will also be a common Nordic capacity market.

Fingrid

The mFRR capacity is procured on an hourly resolution and the market closes at D-1 in the morning. All capacity is paid the price of the highest accepted bid (marginal price). The procured capacity must be bid to the mFRR energy market, where it will be handled by the same rules as voluntary energy bids. To secure upregulation capacity, Fingrid also has reserve power plants at its disposal. They are activated only after energy bids from BSPs have been activated.

Svenska kraftnät

Svenska kraftnät has a national capacity market where mFRR is procured for all bidding zones, both up- and down-regulation. The mFRR capacity market operates on a daily basis with hourly resolution. Gate-closure-time is the day before operation, before closure of the day-ahead market. All capacity is paid in accordance with the highest accepted bid (marginal price). The procured capacity must be bid to the mFRR energy market, where it will be handled by the same rules as voluntary energy bids.

In addition to this, Svenska kraftnät procures a specified volume of mFRR capacity on long term contracts. In case of a large disturbance, this capacity can be activated as a fall-back solution when the volume of voluntary energy bids is insufficient. This capacity is procured in bidding zones SE3 (Stockholm) and SE4 (Malmö). The capacity is procured on long term contracts (1 year or longer) with market actors that guarantee a certain capacity to be available for full activation within 15 min at any given time. This reserved capacity must be larger than the national reference incident, which usually is a nuclear power plant of around 1450 MW. Currently, the capacity is supplied by a collection of power plants, mostly gas turbines. Most of these long term contracts will have expired by the end of 2024.

Energinet

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For DK1 Energinet procures mFRR from a capacity market only for up-regulation. The mFRR capacity market operates on a daily basis per hour. Gate-closure-time is the day before operation, before closure of the day-ahead market. All capacity is paid in accordance with the highest accepted bid (marginal price). The procured capacity must be bid to the mFRR energy market, where it will be handled by the same rules as voluntary energy bids. Currently Energinet secures mFRR capacity only for upregulation.

For DK2 Energinet procures mFRR for DK2 per hour (240 MW) and also per month (360 MW). Energinet is allowed to run a common market between DK1 and DK2, if the HVDC interconnector between the two bidding zones allows it.

Statnett

Statnett uses two markets for mFRR, accepting bids from production and consumption: the common Nordic energy activation market and a national capacity market. The purpose of using the capacity market is to ensure enough bids in the energy activation market, for both up-regulation and down-regulation. The bids in each market must be offered per bidding zone and per hour.

The energy activation market has its gate-closure-time at 21:30 day-ahead, but it is possible to update bids and/or send in new bids until 45 minutes before delivery. The price of the activations are set by marginal-pricing and bids are picked by merit-order. In case of critical grid situations, bids can be omitted and more expensive bids chosen, settled by pay-as-bid. If so, the omitted bids will not be compensated.

The capacity market has two procurement methods. The daily market with hourly resolution, where gate-closure-time is 7:30 D-1. Reserved capacity and prices are published the same day at 8:10. This market considers the current energy situation and constraints in the grid. The second procurement method is a seasonal market, which covers the winter months (normally October/November to April). The bids are valid for the whole season. The start of the procurement will be announced in time before the season starts.

5. Emergency and Restoration measures

Several measures exist that can be utilised in case the power system enters emergency or restoration state.

5.1 Limited Frequency Sensitive Mode

Limited frequency sensitive mode (LFSM) is an emergency power measure, introduced in the connection network codes for generators, HVDC interfaced systems, and demand resources (NC RfG[1], NC HVDC[2] and NC DCC[3]) [4,5,6]. As LFSM is introduced in the connection network codes, which are applicable for new or revised units, the LFSM volume is expected to increase over time as more new assets are built, or existing assets revised, and thus will have this functionality implemented and enabled. LFSM per the connection requirements shall provide a proportional response to the frequency similarly to how FCR operates, but with a larger dead-band than for FCR. LFSM for under-frequencies (LFSM-U) is activated in the frequency range 49.5-49.0 Hz, while LFSM for over-frequencies (LFSM-O) is activated in the frequency range 50.5-51.0 Hz.

While LFSM is a mandatory function, for units affected by the relevant connection requirements, LFSM is not a market-based function and the asset owners are not required to reserve any capacity to ensure the availability of the function. Instead, LFSM will utilize any free capacity that happens to be available at any point in time. For example, wind power parks are often operated at full available power, and hence wind power typically do not provide a significant amount of LFSM-U, since little upregulation capacity exists, even if the controller function is always enabled. Similarly, volumes used for power support on HVDC cables are not reserved, hence only free capacity is used to provide LFSM over HVDC. Because of this, the LFSM function is designed and dimensioned such that the power system shall not be dependent on LFSM to maintain operational security in normal operation or after N-1 incidents.

The Nordic SA can receive support through LFSM from other synchronous areas via HVDC interconnectors[4]. Correspondingly, the Nordics provides LFSM to other synchronous areas through the same interconnectors. The support to continental Europe from the Nordics is active for continental frequencies between 50.2-50.8 Hz and 49.8-49.2 Hz. LFSM over HVDC is a bit of a special case, since HVDC interconnectors between synchronous areas are bi-directional, and the energy contributed to one end is taken form the other end. Thus, the system frequencies are affected in both of the synchronous areas connected to the interconnector which means that the frequency of the area giving support may deteriorate as the frequency of the receiving area is improved. Hence, the volumes for LFSM support over HVDC between synchronous areas are specified in agreements between the affected TSOs. The volumes are spread close to equally between the relevant interconnectors between the other synchronous areas connected to the Nordics, to maximize availability. In the ENTSO-E report "Operational Limits and Conditions for Mutual Frequency support over HVDC" the following volumes are specified as the aim of power support exchange between the synchronous areas:

[1] The NC RfG is not valid in Norway, but Norway has a corresponding set of national requirements.
[2] The NC HVDC is not valid in Norway, but Norway has a corresponding set of national requirements.
[3] The NC DCC is not valid in Norway, but Norway has a corresponding set of national requirements.
[4] The full LFSM support is planned to be implemented in 2025. Meanwhile legacy HVDC interconnectors may utilise Emergency Power Control instead of LFSM, in accordance with section 5.2 below.

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Table 4. Proposed values for system level minimum volumes for support to the Nordics.

Direction of flow seen from the **providers** perspective	**CE** → Nordics	**GB** → Nordics
Over-frequency (in Nordics)	-1000 MW	-400 MW
Under-frequency (in Nordics)	1000 MW	600 MW

Table 5. Proposed values for system level minimum volumes for support from the Nordics.

Direction of flow seen from the **providers** perspective	**Nordics** → CE	**Nordics** → GB
Over-frequency (in other SA)	-500 MW	-500 MW
Under-frequency (in other SA)	600 MW	600 MW

In Figure 4 all HVDC cables that are connected to other synchronous areas from the Nordic synchronous area can be seen. Legacy HVDC interconnectors may utilise Emergency Power Control instead of LFSM, in accordance with section 5.2 below.

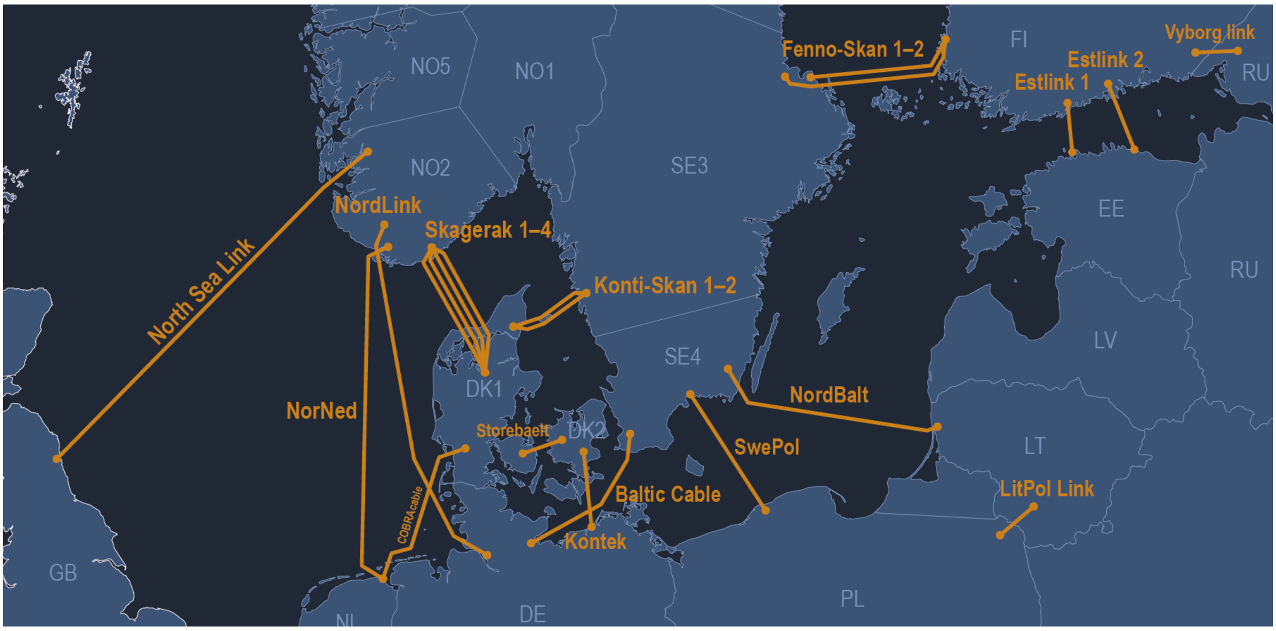

Figure 5. HVDC connectors between the Nordic synchronous area and other synchronous areas.

5.2 Emergency Power Control

An EPC activation is an automatic emergency function that immediately delivers power response to support the system in need. The intention is to prevent a system blackout and avoid disconnection of load or generation. EPC is implemented on several of the HVDC- interconnectors connecting the Nordic power system to other synchronous areas and is activated when the frequency on either side of the HVDC-link reaches critical limits. Normal range of EPC activation in the Nordic system is 49.5-49.0 Hz for under frequency and 50.5 –51.0 Hz for over frequency. Compared to FCR and LFSM, EPCs generally provide a trigger-based step-wise response, more similar to how FFR operates.

In addition to frequency support, EPCs can be utilised to deliver active power to support the power grid in other ways, e.g. voltage stability and remedy over-load of lines.

5.3 Low Frequency Demand Disconnection

Low Frequency Demand Disconnection (LFDD) is a function introduced in Article 15 of the Network Code for Emergency and Restoration (NC ER) [7]. The implementation is further detailed in articles 18, 47 and the Annex of NC ER. Low Frequency Demand Disconnection is sometimes called Under Frequency Load Shedding (UFLS).

If the frequency reaches critically low levels, the LFDD is an automatic function designed to disconnect consumption to avoid a total or regional system blackout. By avoiding a blackout, the restoration of the power system will be much easier. The LFDD function of the Nordic power system is activated shortly after the full activation frequency of LFSM-U. The first step of the load disconnection of LFDD is taken at 48.8 Hz, whereas steady-state full activation of LFSM-U is reached at 49.0 Hz. An updated LFDD activation plan has been introduced in the Nordics with a transition is currently in progress. In the updated plan there are five steps, respectively at 48.8, 48.6, 48.4, 48.2 and 48.0 Hz. The first four steps shall be designed to disconnect at least 5% of the consumption, per step. The fifth step shall disconnect more than 0% of the consumption.

It should be noted that no similar function to LFDD exists for over-frequencies, where LFSM-O is the last resort.

5.4 Manual Demand Disconnection

Manual demand disconnection is an emergency measure that can be used, directly by the TSO or indirectly through DSOs, to prevent the propagation or worsening of an emergency state. It can be used to resolve overloads or under voltage situations, as well as to resolve situations in which assistance for active power has been requested but is not sufficient to maintain adequacy in day-ahead and intraday timeframes in its control area, leading to a risk of frequency deterioration in the synchronous area.

In the case of violation of operational security limits each TSO shall instruct/execute demand disconnection without undue delay if:

1. one or more operational security limits are violated or Total Transfer Capacity (TTC) is exceeded; and
2. one or more control areas have insufficient access to mFRR to mitigate the situation; and
3. other mitigating measures cannot be found

In the case of frequency deterioration in the synchronous area each TSO shall instruct/execute demand disconnection without undue delay if:

1. Activation of all remaining available mFRR have been instructed; and

2. there is a falling/raising trend of the frequency in the synchronous area; and
3. steady state frequency falls below 49.90 Hz or raises above 50.10 Hz; and
4. other mitigating measures cannot be found.

Demand disconnection shall be executed by the TSO which has the largest lack of reserves in its control area according to the net reserve situation. The net reserve situation is defined by the difference between available mFRR and the imbalance. If there are bottlenecks in the system, the demand disconnection shall be planned for in that part of the Nordic synchronous area that relieves the bottlenecks.

The Manual demand disconnection procedures are introduced in article 22 of NC ER [7]. Another name sometimes utilised for the procedure is Manual load shedding.

6. Operational aspects of frequency control

The TSOs aim to keep the system in normal state at all times by procuring the needed volumes of the different reserves, often in advance. It is, however, important to monitor the power system in real time to make sure the frequency is within the limits for normal operation. In the control centres of the Nordic TSOs, operators monitor the power system status by using supervisory control and data acquisition systems (SCADA systems) that continuously receive real time data. The SCADA system will directly inform the operators if there is a disturbance in the power system.

To achieve normal state for the frequency, the operators need to secure both the actual frequency and also the expected frequency in case a disturbance would occur. Even if the TSOs have planned and procured reserves to stay in normal operation things can change during the operational hour, the kinetic energy can be lower compared to forecast, etc. This may result in a frequency outside the allowed limits if a disturbance was to occur.

6.1 Actual frequency

The operators closely observe the trend of the actual frequency in the power system and also the activated volume of aFRR. When needed, they activate mFRR to restore both the FCR, aFRR and the frequency to 50 Hz to be able to handle a new disturbance. It is important to activate mFRR bids in the correct location in the grid not to overload the power lines in the bottle necks. Such a restriction may make it impossible to activate all available mFRR bids as some of them are located behind a grid congestion. Location of FCR and aFRR bids is considered in the security margins when determining the capacities for the corridors between bidding zones for the energy markets.

To minimize the imbalance caused by the change between market time units the operators can initiate power adjustments. This means that when the operator perceives a large difference between two trading periods, the operator can move either planned increased power or planned decreased power ahead of time. This will even out the power difference between two trading periods in time and improve the frequency.

If these measures are not enough, emergency and restoration measures may be utilised, as introduces in section 5.

6.2 Frequency after a disturbance

To ensure a secure operation of the power system the operators must also consider what will happen if the reference incident would occur. This is done by monitoring the frequency in case of a disturbance. If the monitoring system predicts the frequency will be outside the limits (as stated in Figure 2), actions must be taken to get the expected frequency back within the limits. Actions for alert state are either to increase the volume of FFR or to limit the reference incident, as explained in Chapter 1.2.

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7. Future changes to frequency control

In this chapter a few of the future changes to the frequency control are explained. There are currently several changes affecting the operation of the Nordic power system, both regulatory and technical aspects. The technical changes are related to the changes in electricity production and the impacts that will have on the frequency control.

To accommodate these changes the Nordic TSOs have initiated several changes to the frequency control and balancing process. Three of the major changes are explained below.

7.1 Nordic Balancing Model (NBM)

The Nordic region faces some essential changes in the energy market in the next years, requiring a novel method how to balance frequency in future. To cope with upcoming changes while maintaining today's Nordics welfare, the Nordic TSOs are working together in the Nordic Balancing Model program (NBM). More information can be found on this web-page: https://nordicbalancingmodel.net/

The new balancing model is needed in order to enable the shorter Imbalance Settlement Period (ISP), which will go down from today's 60 minutes to 15 minutes, the connection to EU's balancing platforms PICASSO (aFRR) and MARI (mFRR) and new pricing rules. The shorter ISP leads to both an increase in work and less time to act for an operator. The process requires automation to support the operators in decision making. The core part of this automation is a new Activation Optimisation Function (AOF). The AOF will assist to determine the best bids to balance the system, taking the prices and available transfer capacity into consideration. The AOF will use the Area Control Error (ACE) in the respective bidding zone instead of just using the system frequency as today. ACE is representing the power imbalance for a bidding zone, the difference between planned power transfers and actual flow. Figure 6 illustrate this change from frequency based balancing to ACE based balancing.

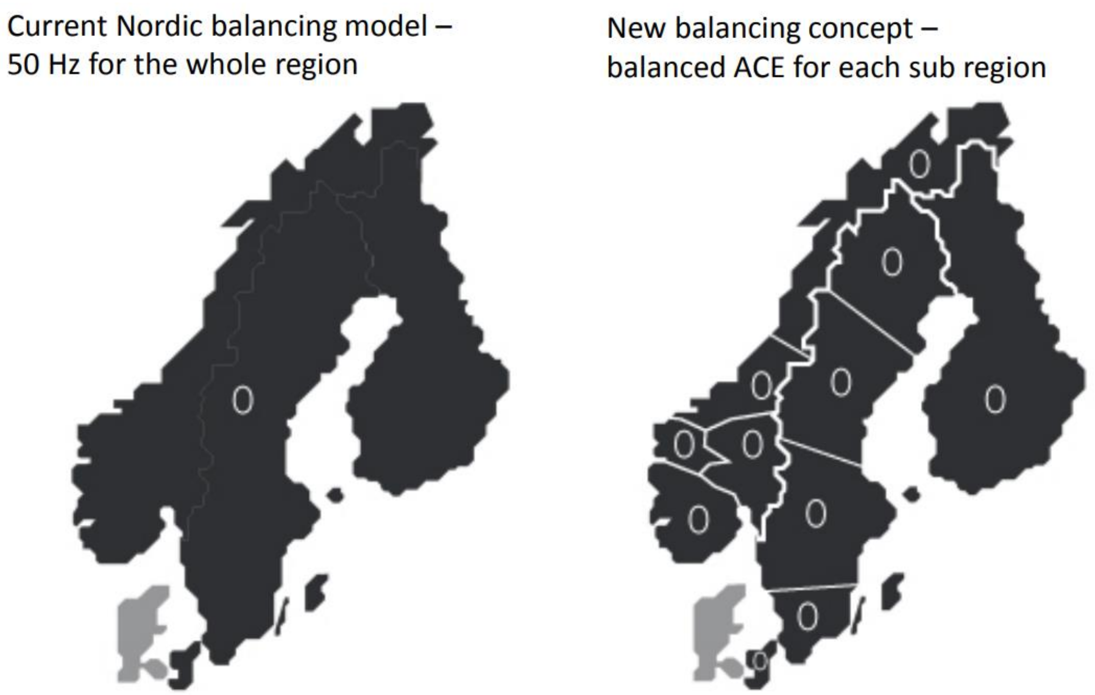

Figure 6: Left: Current Nordic balancing model where only frequency is considered. Right: New balancing concept where the balancing is carried out using the ACE of every bidding zone.

These new circumstances require automation of the processes around bidding and activation. The providers will, for example, need to send additional bid attributes so that the AOF can function. The automated process also makes it possible to accept lower bid size. Table 6 clarifies some of the differences with NBM compared to the current process.

Table 6: Summary of the differences of the NBM concept compared to today's balancing processes.

	Today	**NBM**
Working method	Manual	Mostly automated
Balancing platform	Nordic Regulation Power Market	aFRR (PICASSO) mFRR (MARI)
Imbalance Settlement Period (ISP)	60 min	15 min
Balancing principle	Load Frequency Control blocks	Area Control Error (per bidding zone ACE)
Power flow simulation	NA	Zonal network model
Activation of bids	Nordic merit order list	AOF
Congestion Management	Manual	Automated bid filtering to avoid congestions (eventual activation of bids which positively contribute to congestion management)

7.2 Updated technical requirements for Frequency Containment Reserves

The Nordic TSOs have been developing new requirements for FCR-N and FCR-D in a series of projects. The performance requirements have been updated and stability requirements introduced for both FCR reserves. The updated requirements entered into force in September 2023. The performance requirement have become faster to reflect the need of the power system with a lower kinetic energy. Stability requirements were introduced in order to ensure that the FCR response will have an appropriate stability margin and does not increase the risk for frequency oscillations. The updated requirements also include other new aspects such as FCR provision from aggregated resources.

From September 2023 to September 2028 the Nordic system will be in a transition period, where FCR providing units will move towards the new requirements as their prequalification will become outdated (valid for a 5 year period). This means that the full effect of the new requirements of FCR will not be seen in the Nordic system before the transition period is fully over.

7.3 LFSM on HVDC interconnectors

In the next years, low inertia situations are expected more often in all of the European synchronous areas (SA) due to e.g. a higher penetration of renewable power sources, which are often non-synchronously connected to the power grid. The deterioration of system inertia causes higher risk to system security, in particular to frequency deviations following a large system loss (N-2) which the normal state measures are not fully dimensioned for. To mitigate this risk the TSOs of the SAs of UK, Continental Europe and Nordics are planning to implement mutual frequency support using LFSM on HVDC links between the SAs. The tentative time plan is that the implementation shall be finished by the end of 2025. At the moment the Baltic and Irish SAs are not part of this agreement.

When LFSM is implemented, it is mainly recommended to utilise a droop based response, where technically feasible. Otherwise, a step based response utilising pre-existing EPCs may be used to approximate a proportional response.

Additional information on LFSM over HVDC can be found in chapter 5.1.

8. Finalized Nordic projects regarding frequency control

Over the years the Nordic TSOs have performed several projects related to frequency in order to achieve a good level of power system security. These projects had different topics like frequency oscillations, frequency quality, inertia, FCR, LFDD, etc. A selection of recent project reports is shown below.

FCR:

- Technical Requirements for Frequency Containment Reserve (September 2023)
  https://www.fingrid.fi/globalassets/dokumentit/fi/sahkomarkkinat/reservit/technical-requirements-for-frequency-containment-reserve-provision-in-the-nordic-synchronous-area.pdf
- FCR-Design (January 2019)
  https://www.statnett.no/globalassets/for-aktorer-i-kraftsystemet/utvikling-av-kraftsystemet/nordisk-frekvensstabilitet/fcr-d-design-of-requirements--phase-2.pdf

Inertia:

- Future System Inertia (2016)
  https://eepublicdownloads.entsoe.eu/clean-documents/Publications/SOC/Nordic/Nordic_report_Future_System_Inertia.pdf
- Future System Inertia 2 (2017)
  https://www.statnett.no/globalassets/for-aktorer-i-kraftsystemet/utvikling-av-kraftsystemet/nordisk-frekvensstabilitet/future-system-inertia-phase-2.pdf.
- Fast Frequency Reserve – Solution to the Nordic inertia challenge (December 2019)
  https://www.fingrid.fi/globalassets/dokumentit/fi/sahkomarkkinat/reservit/fast-frequency-reserve-solution-to-the-nordic-inertia-challenge.pdf
- Fast Frequency Reserve – Design of requirements (February 2020)

  https://energinet.dk/media/rwbbyspn/1c-ffr-design-requirements-external-document.pdf
- Fast Frequency Reserve – Technical requirements (Version 1.1) (January 2021)

  https://www.svk.se/siteassets/english/stakeholder-portal/prequalification/technical-requirements-for-ffr-v1.1.pdf

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Revision index

Ver.	Significant updates	Date	Approved by
1.0	First submission	2021-08-26	NAG / RGN
1.01	Updated outdated information throughout the document	2022-03-15	NAG
2.0	Added section related to emergency and restoration measures	2023-02-24	NAG / RGN
2.1	Updated outdated information throughout the document	2024-04-19	

More information

- https://www.statnett.no/for-aktorer-i-kraftbransjen/systemansvaret/kraftmarkedet/reservemarkeder/
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References

Ref.	Document name and designation
1	System Operation Guideline (SO GL) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32017R1485
2	Electricity Balancing Guideline (EB GL) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2017.312.01.0006.01.ENG&toc=OJ:L:2017:312:TOC
3	Nordic System Operation Agreement (SOA) – Annex Load-Frequency Control & Reserves (LFCR), https://eepublicdownloads.entsoe.eu/clean-documents/SOC%20documents/Nordic/Nordic%20SOA_Annex%20LFCR.pdf
4	Network code on Requirements for grid connection of Generators (NC RfG) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:JOL_2016_112_R_0001
5	Network Code on Demand Connection (NC DCC) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2016.223.01.0010.01.ENG&toc=OJ:L:2016:223:TOC
6	Network code on requirements for grid connection of High Voltage Direct Current systems and direct current-connected power park modules (NC HVDC) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32016R1447
7	Network Code on electricity Emergency and Restoration (NC ER) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2017.312.01.0054.01.ENG&toc=OJ:L:2017:312:TOC

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