European Network of
Transmission System Operators
for Electricity

Fast Frequency Reserve – Solution to the Nordic inertia challenge

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Contents

Abbreviations and Symbols

Abbreviations

EMS	Energy Management System
f	Frequency
FFR	Fast Frequency Reserve
NAG	Nordic Analysis Group
N-1	Single worst possible disturbance / Reference incident
RoCoF	Rate of Change of Frequency
RGN	Regional Group Nordic
SCADA	Supervisory Control And Data Acquisition
SOGL	System Operation Guideline
SA	Synchronous Area
STD	Standard deviation

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1. Introduction

This report summarises the solution to the transient frequency stability challenge in the Nordic synchronous area. Various options to address the challenges have been considered and assessed. Increasing the inertia level is not the only measure to secure frequency stability. In the Nordic synchronous area securing frequency stability will in the future be ensured by introducing a new fast reserve, Fast Frequency Reserve (FFR), as a complement to the primary reserve for disturbances (FCR-D). FFR takes over as the first mitigation measure at situations with low inertia and large reference incident [1].

To maintain operational security of the power system its frequency must lie within a predefined range, and not deviate too far from the frequency for which the system was designed. If the frequency is not held near its nominal value, protection systems begin to activate to protect machinery, and to keep the power system operational.

Large deviations in frequency are often caused by the tripping of large production units or HVDC-links connected to other synchronous systems, which result in sudden imbalances in generated and consumed active power. Frequency can then drop to an unacceptable level, resulting in the disconnection of production units and loads, producing a cascade effect, which may lead to widespread power outages. As production units and HVDC-connections become larger, greater imbalances will arise, resulting in potentially larger frequency deviations.

Synchronous generators help the power system to resist changes in system frequency. All synchronously connected rotating machines contribute to this resistance with their kinetic energy. However, as renewable production begins to replace conventional production, the ability of the system to resist these changes decreases. Modern generating plants such as wind and solar power plants comprise of generating units which interface to the power system through frequency converters. These converters, however, are most often controlled in such a way that operation of the generating plants is independent of the system frequency, resulting in reduced system inertia. Power system inertia is defined as the ability of a power system to oppose changes in system frequency due resistance provided by rotating masses. Inertia is dependent on the amount of kinetic energy stored in rotating masses connected to the system. The same is true of motor loads which utilise power electronics.

It is expected that electricity will be produced more and more by wind and solar power plants. Additionally, thermal power plants will spend less time synchronised to the power system. Load characteristics are also expected to continue to change, with rotating motors being connected to the power system through frequency converters. High import on HVDC connections to other synchronous systems is also expected to replace traditional production more often. These factors will impact system kinetic energy [2].

It is of interest to know the amount of system kinetic energy to operate the system securely and as efficiently as possible since the behaviour of frequency in the Nordic power system is highly dependent on the amount of kinetic energy in the system. Previous projects have investigated and explored the relation between power system behaviour and the system inertia, *Future System Inertia* phase 1 [2], and how to anticipate and to avoid the effects of low-inertia situations, by means of proper forecasting tools both short and long term and mitigation measures, *Future System Inertia 2* [3]. Various mitigation measures of low-inertia situations are proposed in the latter report and tested on their efficiency. An overview is provided in **Figure 1**.

The reduction of the dimensioning incident, a measure already existing today, scores low in terms of cost and can be seen as a "plan B". The "plan A" mitigation measures – being most promising in terms of potential, effectiveness, being sufficient, and cost that can be available in 2020 – consist of active power injections.

The Regional Group Nordic has initiated the implementation of the Fast Frequency Reserve (FFR) based on the results from previous analysis from the Nordic Analysis Group (NAG), where both RGN and NAG are representing Energinet, Fingrid, Svenska kraftnät, and Statnett, i.e. the Nordic TSOs who are responsible for the Nordic synchronous system. The FFR is to be implemented on a Nordic level by summer 2020.

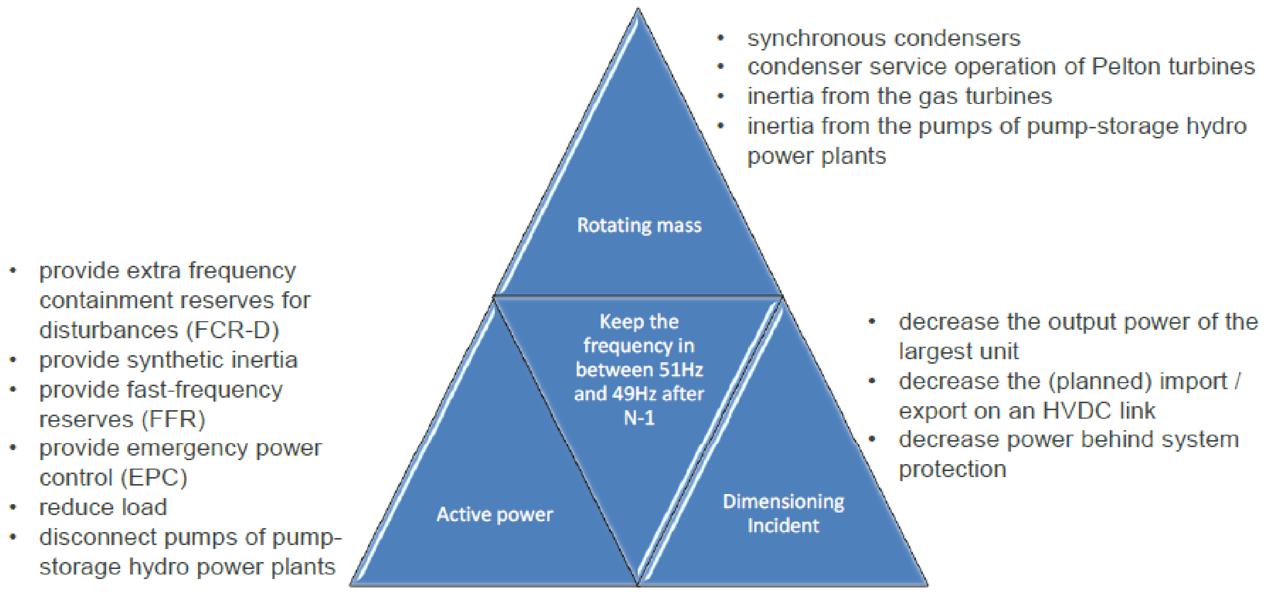


***Figure 1** – Low inertia mitigation measures*

2. Justification

Frequency stability is here mainly referred to the ability of securing the frequency above a threshold, in the Nordic synchronous area 49.0 Hz as stated in system operation guideline (SOGL) art. 127, 1 [4], in order not to activate involuntary load shedding, starting at 48.8 Hz, given the reference incident. For the time being, RoCoF is not of high concern in the Nordic synchronous area, however, the concern is maximum instantaneous frequency deviation. The current response of the primary frequency reserves in the Nordic synchronous area does not ensure frequency stability in low inertia situations given the reference incident [1].

In the system operation guideline (SOGL) art. 39.3a [4], minimum inertia in the system may have to be specified, taking into account the costs and benefits as well as potential alternatives. There exist more efficient mitigation measures available in the Nordic synchronous area among the alternative measures than increasing or maintaining the inertia; in conclusion no need to specify a value for minimum inertia [5].

The effects of a reduction of the reference incident, which is currently used as an efficient mitigation measure, is compared with the new reserve called Fast Frequency Reserve (FFR) in [1]. This is analysed in conjunction with new technical requirements of the FCR-D aiming at ensuring frequency stability and closed loop stability (sufficient dampening effect on frequency oscillation) with low inertia in the system, hence the technical requirements for primary reserves are being redesigned in order to guarantee sufficient primary response in the future [6], [7]. Initially, rather strict requirements were proposed which were able to secure frequency stability down to rather low inertia without having to reduce the reference incident nor introduce a faster reserve. This, however, came at the price of having difficulties of pre-qualifying sufficient amount of reserves. Some units could not prequalify at all or had their reserve capacity heavily reduced [1].

As **Figure 2** shows, the amount of kinetic energy (inertia) affects the rate of change of frequency (RoCoF) after a generator trip. Higher inertia means more kinetic energy in the rotating masses of turbine-generator units. As the system frequency decreases, decelerating masses release their kinetic energy to the system and in this way reduce the power imbalance. Hence, the minimum frequency for a reference incident based on the inertia level will be the basis for the action needed. For most hours in the winter there will currently not be a need for any additional actions, due to high inertia levels.

In situations with low inertia, most likely during periods with low demand in the summer, there will be a need for additional action. The preferred solution to handle both the present and future low inertia situations in the Nordics based on costs and benefits for the range of suggested solutions is FFR.

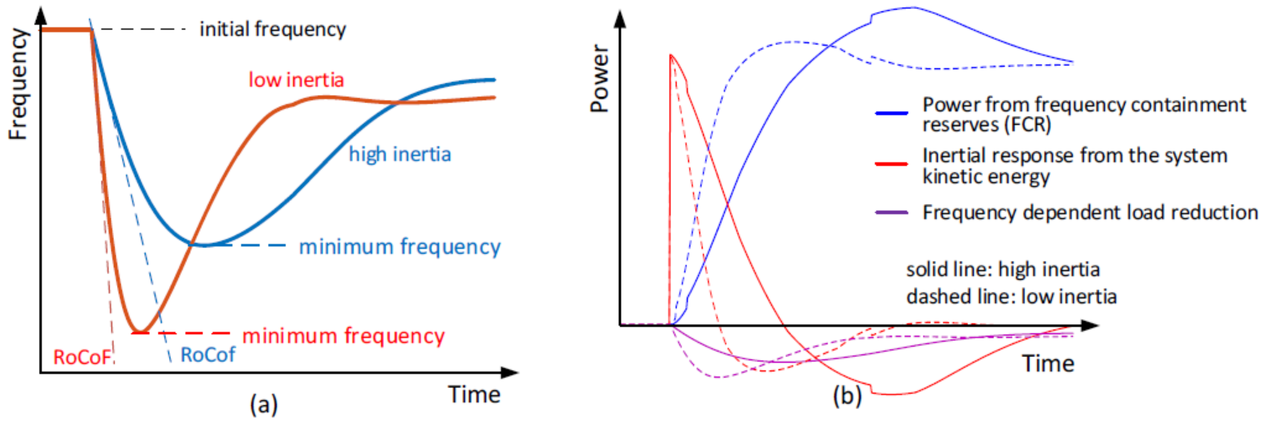


Figure 2 *- Frequency and power responses after a generator trip with high and low inertia*. a) Initial frequency and the frequency after a generator trip. b) Power responses from the kinetic energy (inertial response), from frequency containment reserves (FCR), and from the load reduction of the frequency dependent loads *[5]*.

The possible methods for affecting the initial rate of change of frequency are: 1) the system inertia, and 2) the power imbalance. For the instantaneous frequency minimum, also 3) the speed of the primary reserves comes into play.

Increasing system inertia, i.e. increasing the kinetic energy in the rotating masses of synchronous generators, is a possible solution for maintaining frequency stability. The volume needed to affect the minimum frequency by 0.1 Hz in an 80 GWs system is 20 GWs [3], p. 101. The availability of different possible techniques varies but the costs will be high. Examples of possible techniques are running units as synchronous condensers or starting generators and running them at low output [3], p. 116.

An option the transmission system operators have is to limit the power of the largest generators, loads or HVDC links connected to the system. This option does not require investments but has costs and can be a suitable method during exceptional situations, for example, during short periods when sufficient amounts of reserves do not exist or when the system inertia is exceptionally low. However, reducing the power of a nuclear generator may increase the risk of tripping the generator [5].

FFR is deemed the most promising mitigation measure for low inertia situations since several technologies can provide fast active power response estimated at low socio-economic costs, either as a disconnection of load or fast increase from inverter-based generation and storage. According to the feasibility study [8], FFR is a more cost-efficient measure for handling low inertia challenges compared with reducing the size of reference incident.

3. Technical requirements for FFR

The objective of FFR is to maintain frequency stability. It acts as a complement to FCR-D. FFR does not reduce the need of FCR-D, thus, does not replace FCR-D [9]. Given the framework for the design, there are four main aspects to be considered in the design.

- Full activation time – Faster activation improves the system frequency response
- Activation frequency – Activation at smaller frequency deviation improves the system frequency response but increases occurrence of activation
- Duration – Longer duration extracts more energy from the FFR source
- Deactivation – The combination of abrupt deactivation and short duration may cause the frequency to drop a second time. The risk of a second drop in frequency can be avoided by either extending the duration or requiring smooth deactivation

For all these four aspects, there is a need to consider the balance between the system needs and what different technologies are capable of delivering. There are basic needs the system cannot compromise on: The frequency response must fulfil the system performance requirement ($f > 49.0$ Hz) and shorter full activation time improves the response. The response is also improved by increasing the volume of FFR, if it is sufficiently fast. Increased volume of FCR-D on the other hand does not result in a sufficiently fast response to satisfy the system performance requirement. In order not to have FFR activated for small frequency events and to keep the occurrence of activation low, the frequency threshold must be set low enough. At the same time, in order not to require to fully activate FFR within a very short time, the threshold should not be too low. The design needs to function for the actual frequency response in the current system as well as for the future system with both slightly decreased inertia levels and the new requirements of FCR-D implemented [1].

The design has to be sufficiently fast to handle the worst case in terms of low inertia, however, the volume of FFR is a variable and can be increased in order to meet the system performance requirement. In order to simplify the design and avoid closed loop stability dependency between FFR and FCR-D, the response is designed to be static. Since activation is static, i.e. activation is based on a logic variable which simply actives the response when the frequency drops below a threshold, closed loop stability is not of concern. A static response will also open up the possibility for more providers to deliver FFR [1].

In order to participate in the Fast Frequency Reserve markets, it is necessary for FFR providing units to be prequalified. The pre-qualification process ensures compliance so that FFR providers have the ability to deliver FFR as required by the TSO and that all necessary technical requirements are fulfilled. The pre-qualification shall be performed before a provider can deliver FFR and shall consist of documentation showing that the provider can deliver the FFR as agreed with the TSO. The pre-qualification process includes verification of the properties of the FFR providing entity, accomplishment of pre-qualification tests and monitoring. The prequalification process starts with a notification of the tests from the potential FFR provider to the reserve connecting TSO [9].

The FFR volume is quantified in MW. FFR for underfrequency is defined as a positive value, either as an increase of power infeed to the system or as a load reduction. FFR is intended to be a fast, active power support, responding to a frequency deviation. The requirements on frequency activation level and maximum full activation time are the same for both long and short support duration FFR. The minimum support duration is 5.0 s (for short support duration) and 30 s (for long support duration).

There are three alternatives for the combination of frequency activation level and full activation time, as shown in **Table 1**.

Furthermore, a sequential diagram for the activation, support duration, deactivation, buffer time and recovery period are shown in **Figure 3**.

Alternative	Activation level [Hz]	Maximum full activation time [s]
A	49.7	1.30
B	49.6	1.00
C	49.5	0.70

Table 1 *- Three alternatives for the combination of frequency activation level and full activation time for FFR [9].*

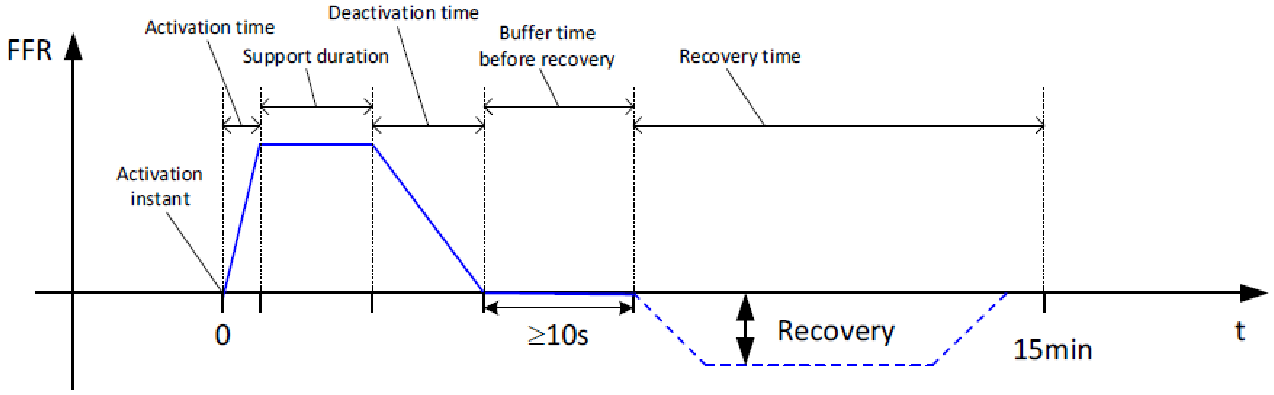


Figure 3 *- FFR activation and recovery requirements; activation time at t=0 [9].*

With respect to **Figure 3**, the following shall be valid:

1) The activation instant is at time equal to zero (0).
2) The maximum time for full activation is 0.70 s (for the activation level 49.5 Hz), 1.00 s (for the activation level 49.6 Hz), and 1.30 s (for the activation level 49.7 Hz).
3) The minimum support duration is 5.0 s (for short support duration) and 30 s (for long support duration).

The prequalified FFR capacity is the minimum support power in MW from the providing entity, within the time slot of the *support duration*. The maximum acceptable overshoot is 35% of the prequalified FFR capacity.

There is no limitation in the rate of deactivation for the long support duration FFR; the deactivation can be stepwise. For the short support duration FFR, the rate of deactivation is limited to maximum 20% of the prequalified FFR capacity per second, as an average over any integration time of one second, and with no single step larger than 20%.

The FFR providing entity must be ready for a new FFR activation cycle within 15 minutes after the activation instant. There is no requirement on the shape of recovery, it may be stepwise. However, the recovery must not exceed 25% of the prequalified FFR capacity and must not start before a time corresponding to the activation time, plus the support duration, plus the deactivation time, plus 10 seconds has elapsed from the activation instant [9].

The technical requirements and prequalification test for FFR are specified in more detail in [9], as well as the requirements on data exchange and data logging.

4. FFR capacity estimation

4.1. Inertia monitoring

To have a real-time grip on the inertia in the system, all Nordic TSOs have implemented a kinetic energy estimation in their supervisory control and data acquisition (SCADA)/Energy Management System (EMS), whereas an online dimensioning incident determination has been implemented in the SCADA systems as well. With these data available, the Nordic TSOs perform an online frequency estimation, in case of a reference incident in the system [3].

The prefault kinetic energy values received from this online estimation system from the years 2017 and 2018 are well above the very low 100 GWs value as shown in **Figure 4**. If a generator trip occurred, the kinetic energy would reduce due to the disconnection of the rotating mass and should be considered in any assessment of the frequency stability.

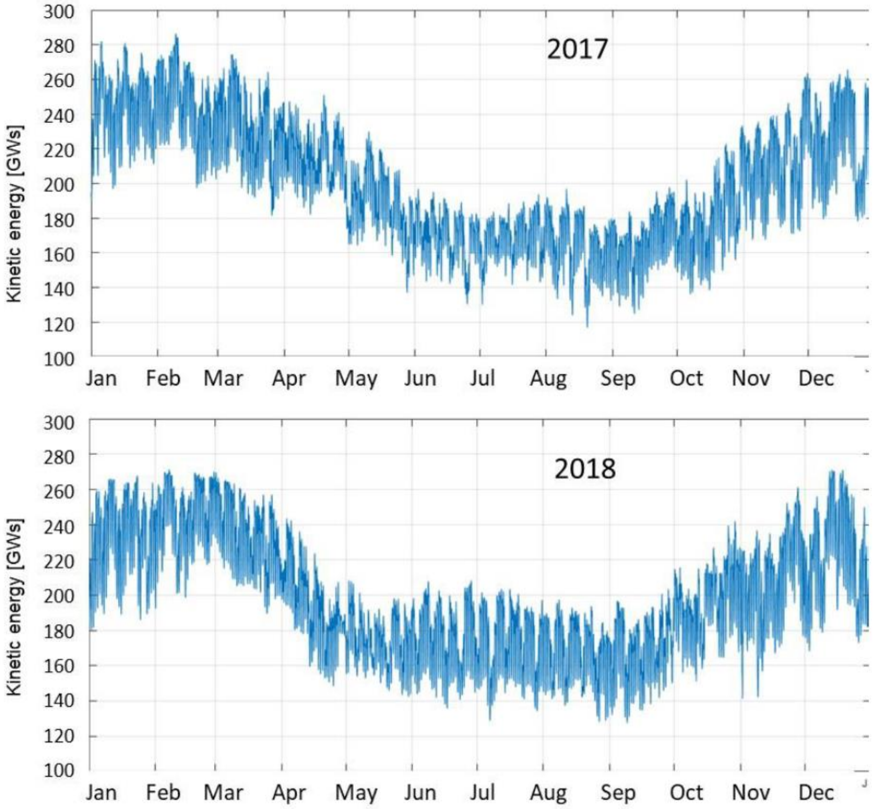


Figure 4 *- Estimated kinetic energy values (pre-disturbance values) from the online kinetic energy estimation tool for the Nordic synchronous system in the years 2017 and 2018 [3].*

Data for the historical inertia levels are shown and can be retrieved on the webpages of the TSOs, i.e. on Fingrid's webpage and on Energinet's webpage.

Future inertia estimations for different future scenarios, presented in [3], show that with 99 % probability, the kinetic energy will be more than 120 GWs or 134 GWs in 2020 and 2025, respectively. Hence, the inertia levels will not change drastically from the present levels and FFR will be a valid solution in the years to come. Svenska Kraftnät has performed long term market simulations for 2030 and 2040 addressing the inertia levels in the more distant future. It concludes that the inertia levels will keep decreasing, hence the need for FFR will increase [10].

4.2. Inertia and frequency minimum forecasting

The aim is to forecast the system inertia in order to estimate the instantaneous frequency minimum for the online reference incident. Two approaches are presented, and the adequateness are for different time frames as it depends on which information is available.

The approach for long term forecasting of the system inertia utilizes market simulations based on the present system for 31 recorded different hydrological years. Generic inertia constants per production type are used to convert the market simulation results to expected system inertia.

The approach for short term forecasting of the system inertia uses production forecasts and production type specific inertia constants. The long term inertia forecast is not as precise as the short-term, since more accurate data can be included in the short term forecast.

To monitor frequency stability based on inertia forecasts and inertia measurements, an empirical model of the frequency response based on occurred disturbances has been created [11].

Using this model, the Nordic TSOs estimate and monitor the instantaneous frequency minimum for a number of specified disturbances in real time. The inputs are the system kinetic energy and the power for each monitored possible disturbance. If the tool estimates an unacceptably low instantaneous frequency minimum, the TSOs need to take actions to improve the situation [1]. Currently, the model is being further developed to increase the accuracy.

4.3. FFR estimated need

Based on historical weather data from 1982 to 2012, and historical inertia data from June 2017 to November 2019, the impact of the variance of the weather data (i.e. hydrological situation, wind speeds, solar irradiation and temperature) on the inertia level in the Nordic SA is analysed. Market model simulations are used to analyse the impact on the inertia based on the different weather years in a Nordic 2020 electricity system. The inertia levels are afterwards on an hourly resolution converted to a Nordic FFR need as explained above.

As shown in **Figure 5**, the Nordic FFR need is impacted a lot by the hydrological situation. One year has a need for FFR in more than 1000 hours, while another year only has a very limited need for FFR in approximately 100 hours. Again, only the weather data is changed in the simulation. The same is shown in **Figure 6** based on historical inertia levels.

The graph showing the FFR need over the course of a year, also reveals that the need for FFR is concentrated around the summer. For the years with high need, FFR is needed from spring to fall as well. The FFR need is highest in the night when the consumption, and therefore production is low.

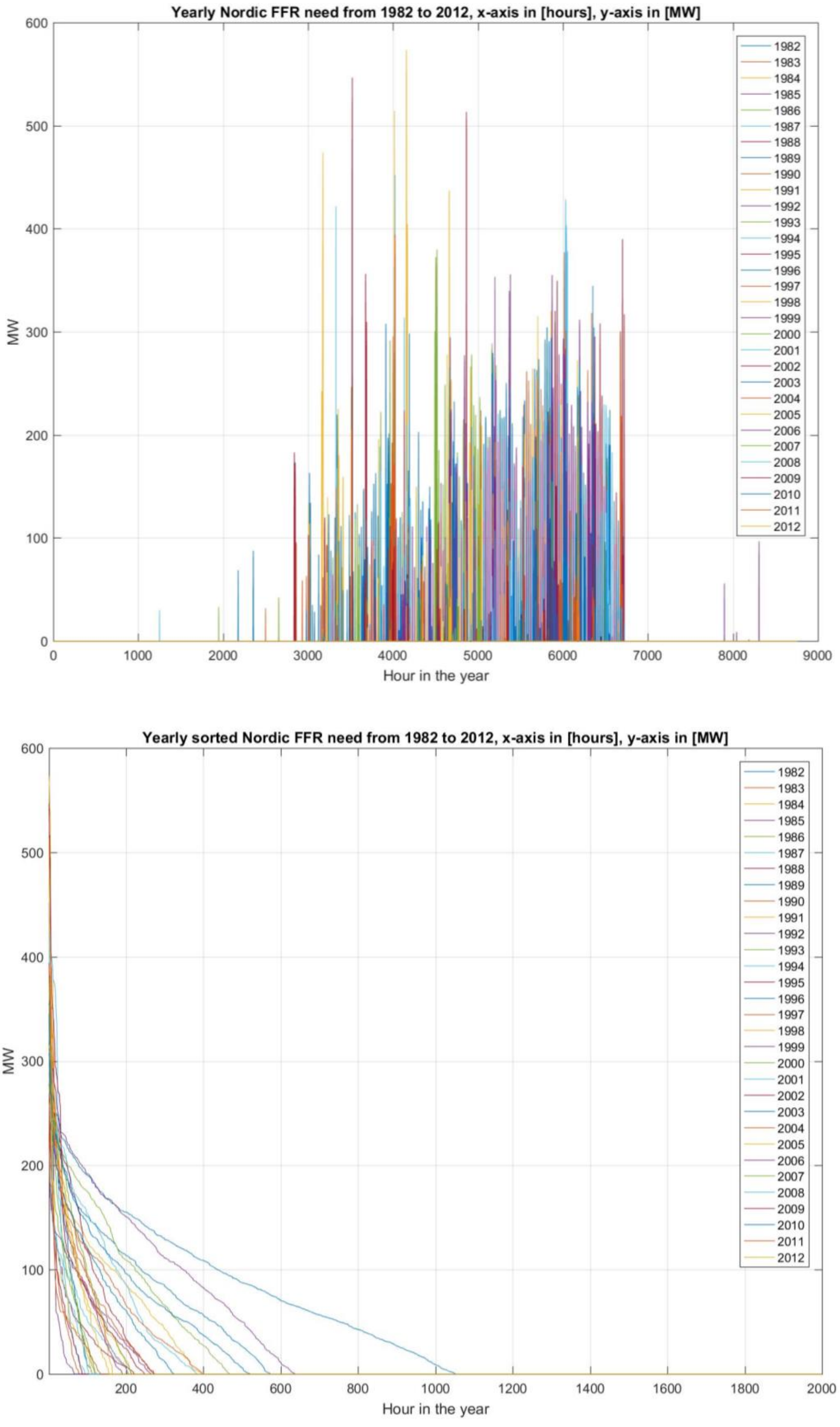


Figure 5 *– Estimated need for FFR in the Nordic SA based upon simulated inertia levels for the present system for 31 different hydrological years. The top graph shows the FFR during the hours over a year and the bottom graph shows the duration curves for the FFR need. Note that the x-axis change.*

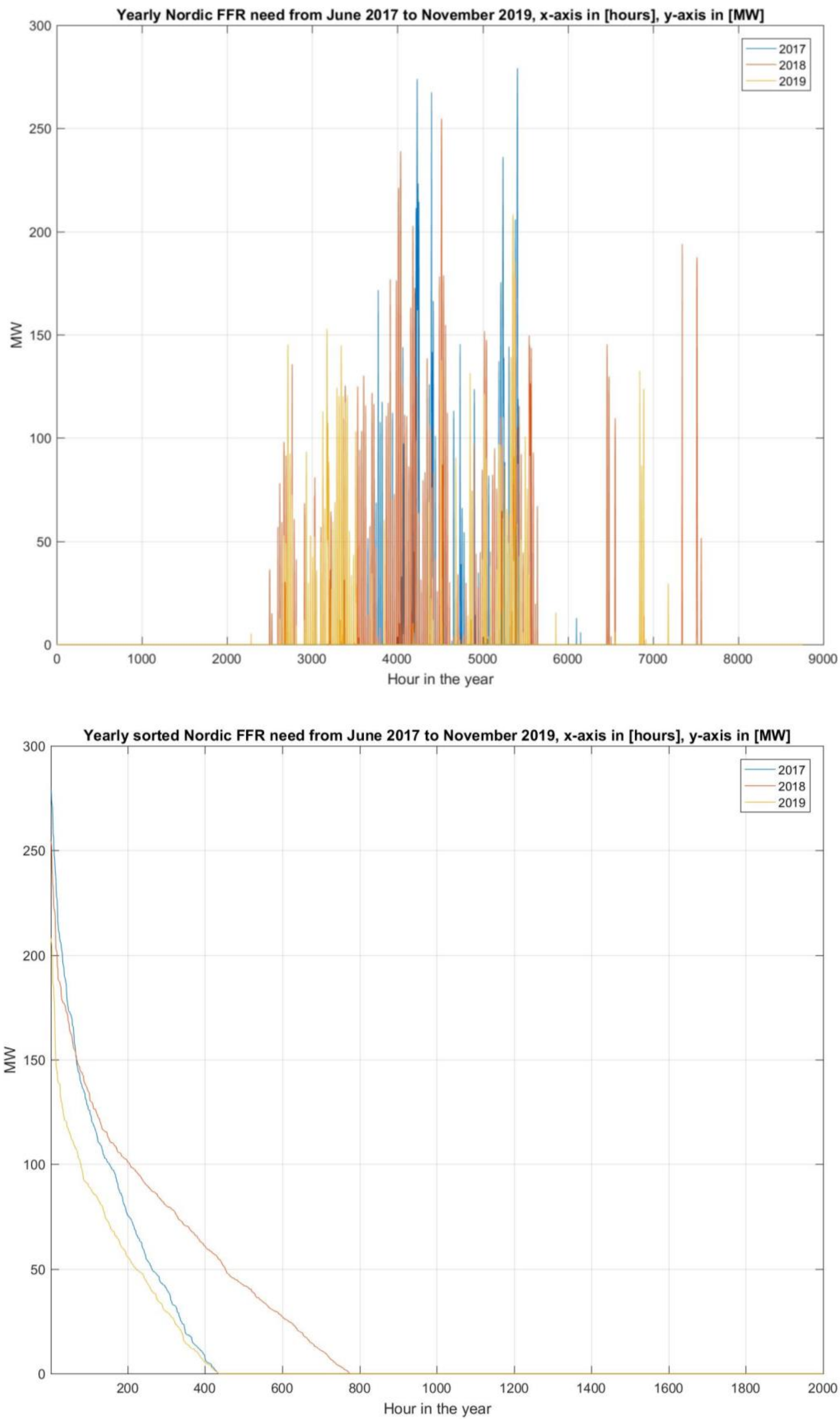


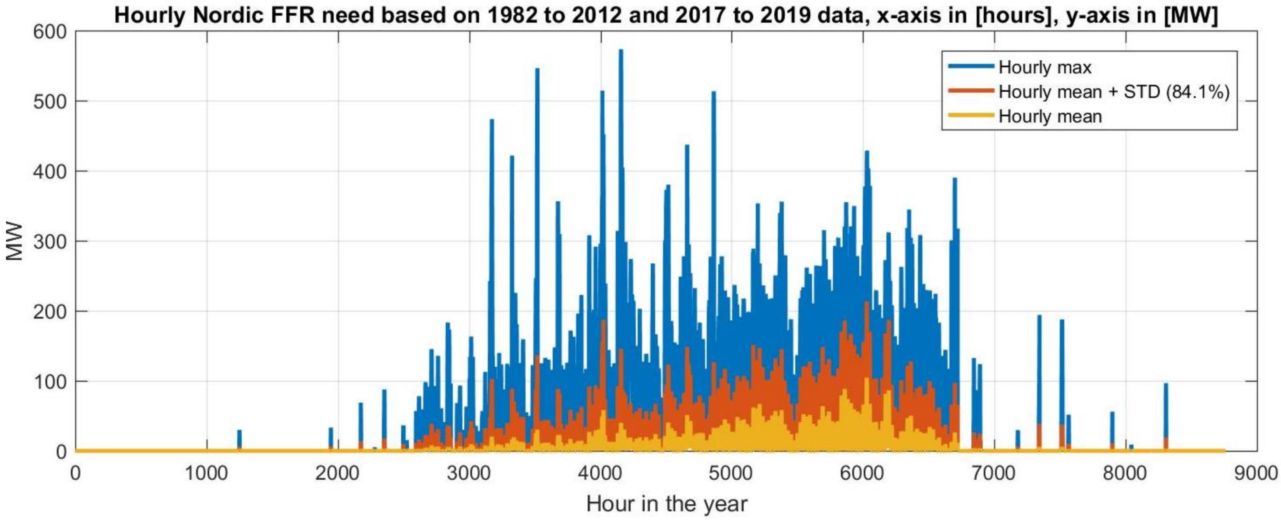
Figure 6 *– Historical need for FFR in the Nordic SA based upon estimated inertia levels from June 2017 to November 2019. The top graph shows the FFR during the hours over a year and the bottom graph shows the duration curves for the FFR need. Note that the x-axis change.*

By utilising the simulation of the 34 years of weather data as a statistical foundation, the probability for the needed amount of FFR can be found as shown for the mean, the mean plus the standard deviation, and the maximum need on an hourly basis for the Nordics in **Figure 7** and the same for the monthly values in **Figure 9**.

Furthermore, the need for FFR is occurring in the weekends and during the night as seen in **Figure 10** and **Figure 11**.

It is also evident from **Figure 10** that there only was a need for FFR for August 2018 (picked randomly) in a very limited amount of hours in the night and during the weekend equal to roughly 15 % of the time.

It is also shown in **Figure 12** below that the extremes, the hour in the 34 years of hydrological data with the highest demand for FFR in the Nordic SA for every hour during the day, are much larger than the 99 % quantile. The 98, 95, 92.5 and 90 % quantiles are also shown in the figure. Furthermore, the need for FFR during the day can also be deduced from the quantiles in the figure.



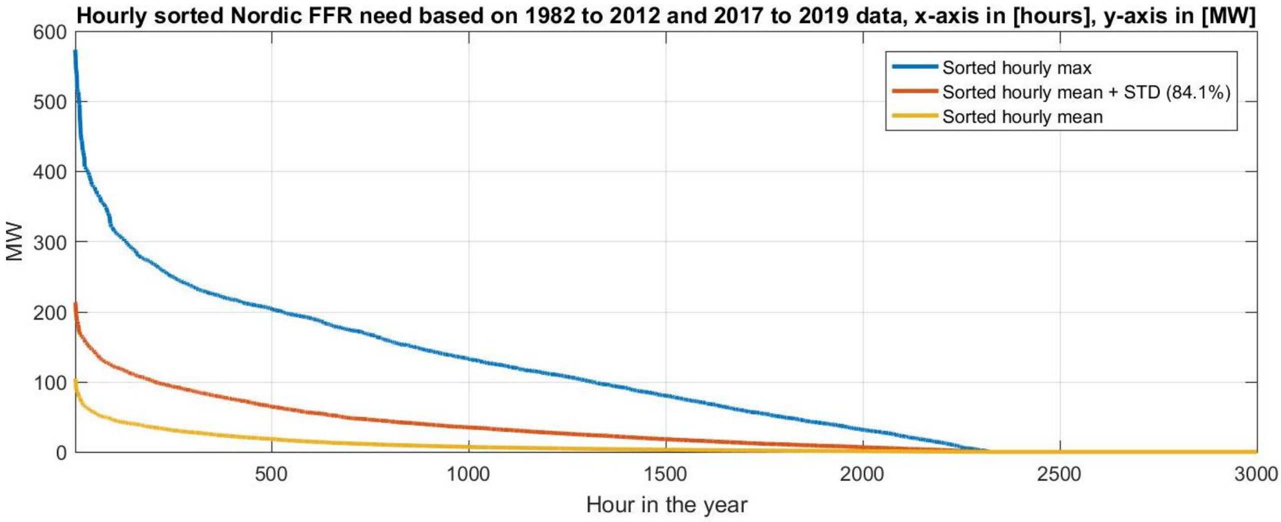


Figure 7 *- Estimated need for FFR in the Nordic SA based upon simulated inertia levels for the present system based on 34 different hydrological years. The top graph shows the FFR during the hours over a year and the bottom graph shows the duration curves for the FFR need. Note that the x-axis change. Both show the average need, the average need plus the standard deviation and the maximum need for every hour in a year (based on the same hour for the 34 simulated years).*

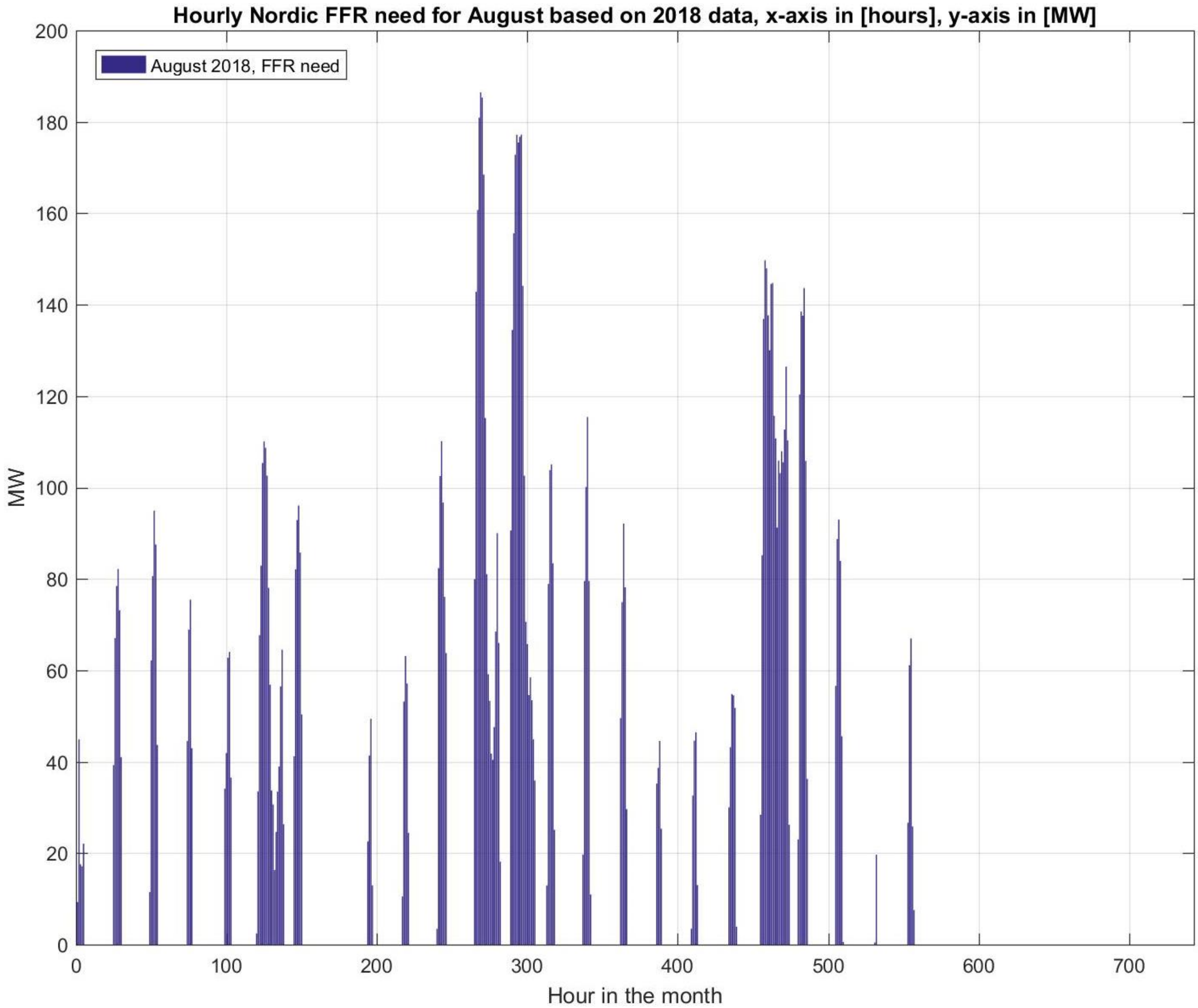


***Figure 8** – Nordic FFR need based on the historical system inertia levels for August 2018.*

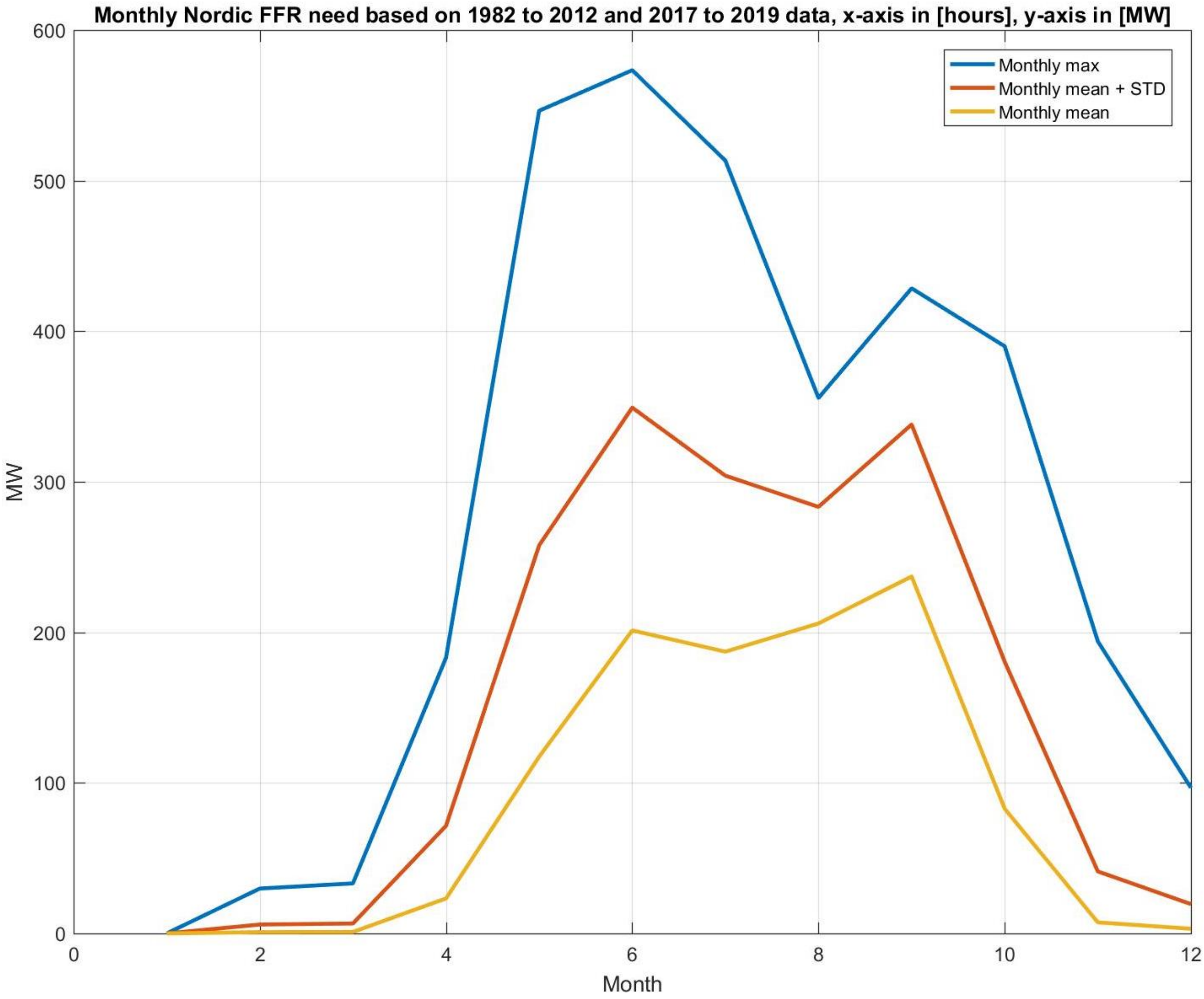
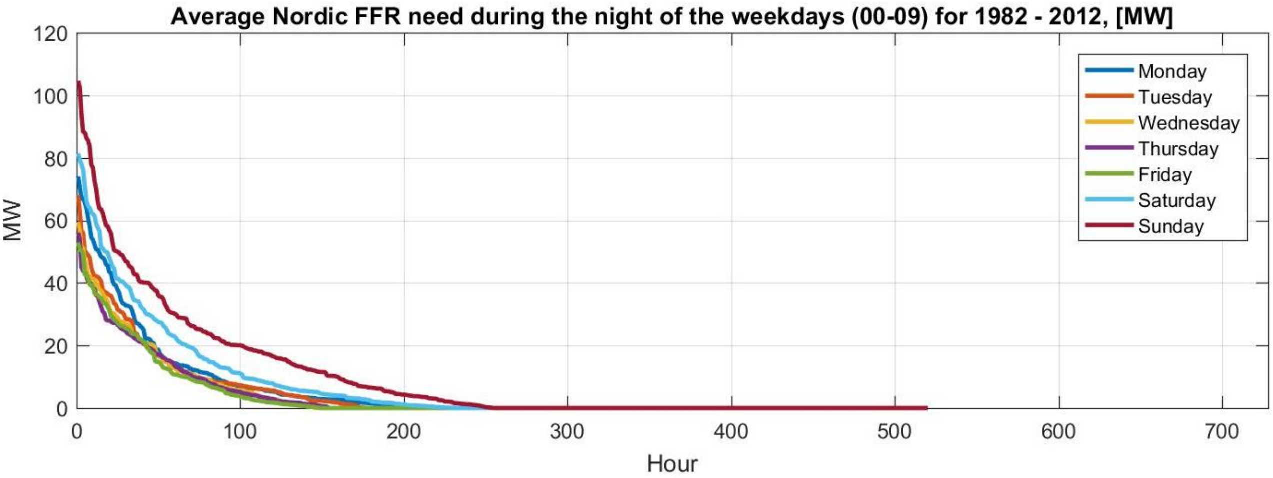


Figure 9 *– Estimated need for FFR in the Nordic SA based upon simulated inertia levels for the present system based on 34 different hydrological years. The graph shows the FFR need during the months over a year, respectively the average need, the average need plus the standard deviation and the maximum need for every month (based on the same hour for the 34 simulated years).*



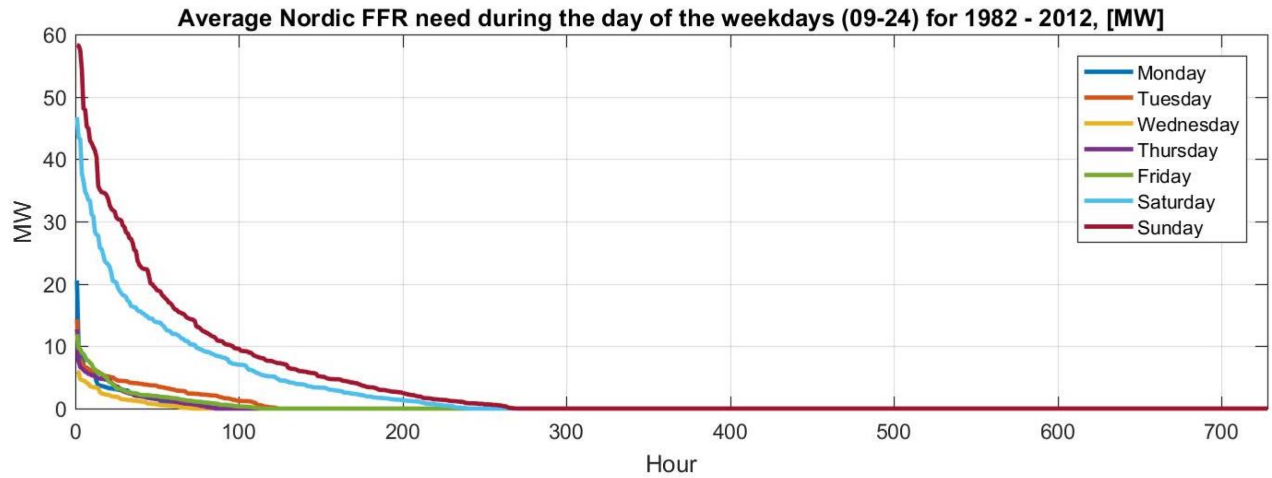


Figure 10 *- Estimated need for FFR in the Nordic SA based upon simulated inertia levels for the present system for 31 different hydrological years, divided into the demand for night and day for the different weekdays. Presented for duration curves.*

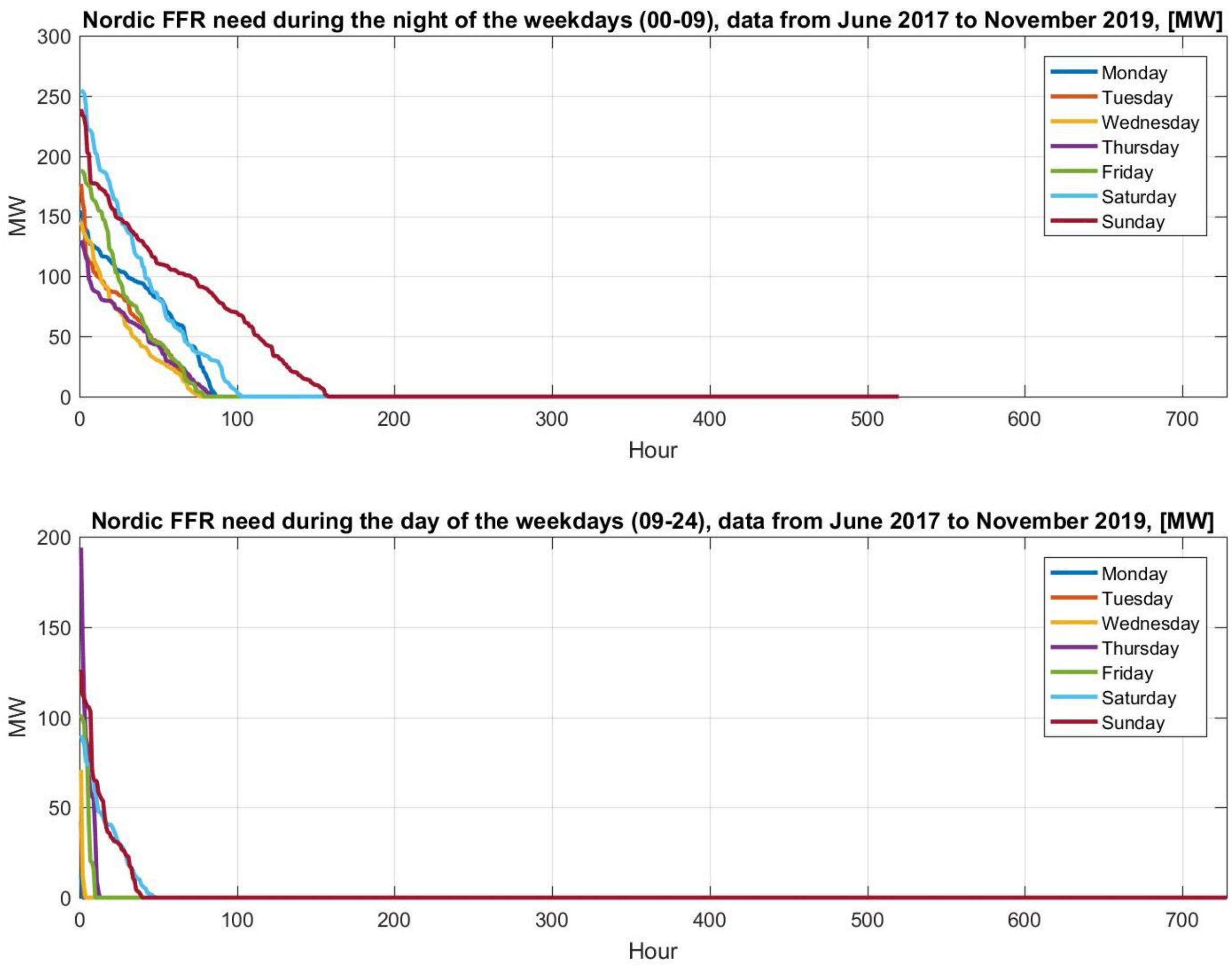


Figure 11 *- Historical need for FFR in the Nordic SA based upon estimated inertia levels from June 2017 to November 2019, divided into the demand for night and day for the different weekdays. Presented for duration curves.*

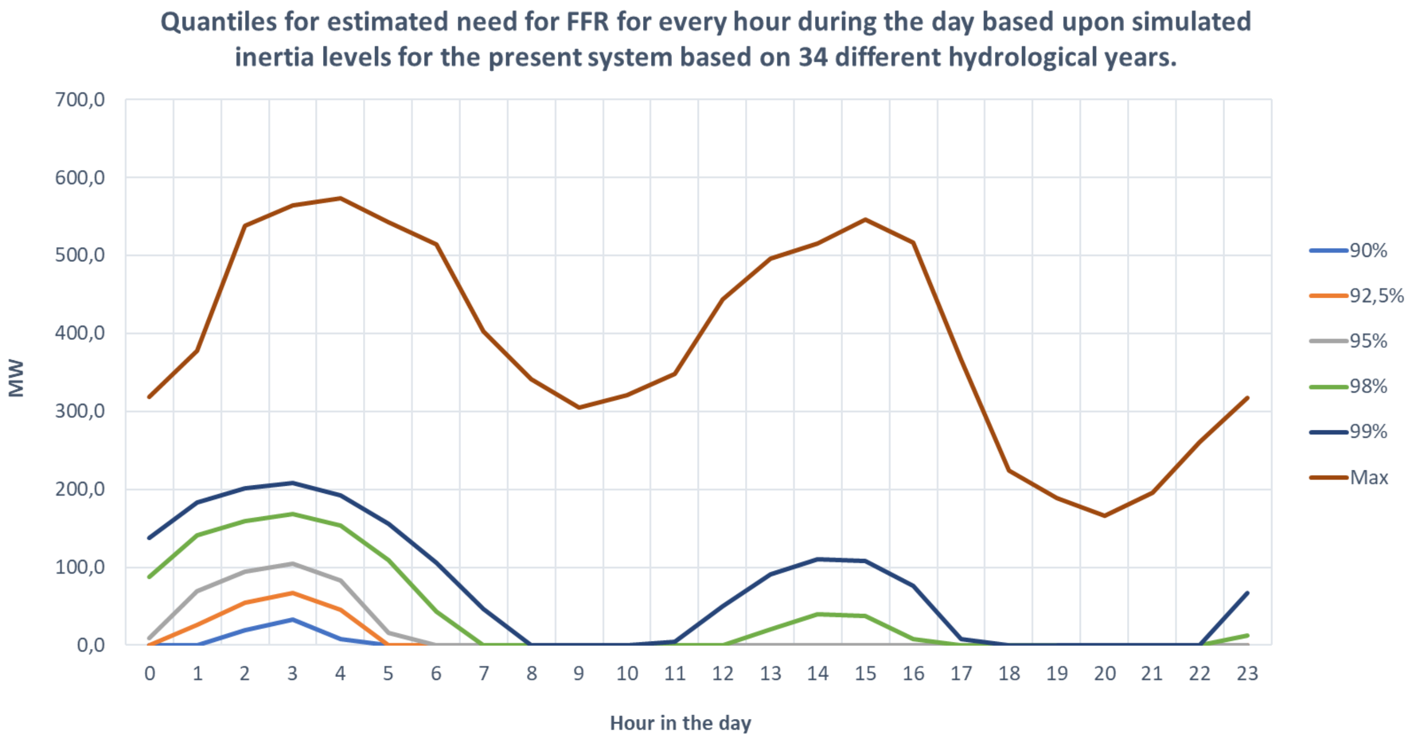


***Figure 12** – 90, 92.5, 95, 98, 99 and 100 % quantiles for the estimated need for FFR for the Nordic SA for every hour during the day based upon simulated inertia levels for the present system based on 34 different hydrological years.*

5. Frequency statistics for the recent years

The frequency crossed the activation threshold values for FFR in 2017 and 2018 very rarely, as shown in **Table 2**. For the full frequency analysis, see report Frequency quality analysis p. 60 and onwards for 2013 to 2018 statistics.

Alternative	Activation level [Hz]	Activation times in 2017 and 2018
A	49.7	9
B	49.6	3
C	49.5	0

***Table 2** – Amount of times when the frequency crossed the activation thresholds for the different FFR alternatives.*

6. National markets & procurement

FFR will be procured on national markets and the market setup will vary between the countries. The sharing key for FFR is based upon the FCR-N/D with a correction factor for the contribution to the inertia and the size of the reference incident of the country. The sharing key to be used during year 2020 is shown in **Table 3**.

FFR sharing key	Energinet	Fingrid	Statnett	Svenska kraftnät
Obligation [%]	14	20	42	24

Table 3 *– FFR sharing key for the procurement of FFR. Division of the Nordic need to the different TSO obligations.*

6.1. Monthly and seasonal procurement

For monthly procurement with a dynamic hourly need, the hour with the largest demand for FFR in the month sets the obligation for the procured amount for the whole month. The same goes for seasonal procurement.

The FFR need during different hours for the coming month/season is forecasted based on the inertia forecast that is based on the statistical variance of the weather for the month/season and the current hydrological situation. The long term inertia forecast is not as precise as the short-term, since more accurate data can be included in the short term forecast. Hence, the procured amount of FFR on a monthly/seasonal basis will most likely be higher than the need for FFR in the actual hour of operation.

As stated it is not possible to precisely forecast the inertia on an hourly basis a month/season in advance. Hence, the monthly procurement must ensure that the FFR need is covered based on a level of statistical probability for every hour in the month/season. By utilising market model simulation of the 34 years of weather data as a statistical foundation, the probability for the needed amount of FFR can be found, as explained in Section 4.3.

6.2. Energinet

The national market in Energinet (for DK2 only) is proposed to be based on monthly capacity auctions until hourly procurement is possible. Hourly procurement demands an implementation of new IT solutions to handle the auctions on a daily/hourly basis.

The energy activation, if any, will be settled at the imbalance price.

Energinet will utilize the D-2 inertia forecast to “free” capacity procured on monthly basis, as explained below. Operating with monthly/seasonal procurement gives the opportunity to allow the provider to reduce the actual capacity to be delivered in a specific hour where the monthly/seasonal procured volume is larger than the actual need. This will “free” capacity for every hour where the monthly/seasonal forecast for FFR is larger than the actual hourly need for FFR.

For a contracted amount from the monthly/seasonal capacity auction of i.e. 10 MW, the short-term inertia forecast could reveal that the need from that provider is only half, hence 5 MW, during a specific hour or day. The “freed” capacity is the difference between the monthly/seasonal procured amount and the short-term forecast. The FFR need from the short-term forecast is specified on an hourly resolution two days before operation, to give the possibility for the TSO to allow for the provider a chance to trade in the day-ahead market accordingly and to allow the “freed” capacity to participate in other reserve markets if relevant. Hence, the available FFR capacity that the provider must deliver could be based on the short-term inertia forecast, with a max of the monthly/seasonal contracted amount and a minimum of zero.

6.3. Fingrid

Fingrid will implement an hourly FFR-market with daily procurement. The procurement need will be calculated daily based on a short-term inertia forecast. Bids are accepted in merit order, where the last accepted bid sets the price of FFR (marginal-cost pricing). Compensation will be for the FFR-capacity only (no energy/activation compensation). The market setup will include possibility of submitting combined FFR and FCR-D bids which enable resources capable of providing both FFR and FCR-D to be utilized in the market where the value of the resource is the highest.

For further information about the Finnish FFR-market, see Fingrid's webpages (at the time of writing available in Finnish only, English version to come).

6.4. Statnett

Statnett is going to implement a seasonal marked for FFR. Providers can offer FFR for the entire season or just for parts of the season. FFR capacity will be procured for the night hours, when low inertia values are expected the most. The procurement takes place in the end of Q1/2020. Reserve capacity bids are accepted in merit order, where the last bid sets the price for the FFR market (marginal-cost pricing). The Norwegian FFR market will pay for FFR capacity as well as for activating the FFR volume. For activation "pay-as-bid" will apply, and the bid prices must reflect actual costs for the provider and cannot be chosen arbitrarily.

Statnett will not pay for contracted FFR capacity in case of non-delivery in parts of the contract period.

Statnett's needed FFR capacity will be derived from the distribution key and a statistical parameter based on the data shown in Figure 5.

Statnett publishes updated information on the FFR website, via "Landsentralen" messenger service and directly by mail for interested providers. Request shall be sent to FFR@statnett.no.

6.5. Svenska Kräftnät

Svenska kraftnät will develop a new market solution for FFR, and in order to be able to deliver a new market solution to April 2020, Svenska kraftnät needs to work in two parallel tracks based on the fact that it is a very tight deadline.

Svenska kraftnät will work to implement a long-term sustainable solution for procurement of FFR, but also to implement an interim solution as of April 30, 2020.

The proposal for an interim solution is that Svenska kraftnät procures FFR from Fingrid or other TSOs to ensure that there is FFR in the system as of April 30, 2020 and the proposal for a long-term solution is for Svenska kraftnät to carry out monthly or seasonal procurement in the Swedish market.

Svenska kraftnät believes that monthly or seasonal procurement is the market solution that will give the best results from suppliers as we do not need enough volume today and not all the hours of the year all year around.

Svenska kraftnät will work with both of the above-mentioned solution proposals in parallel to reduce the risk that the interim solution will be a long-term solution.

7. References

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