European Network of
Transmission System Operators
for Electricity

REQUIREMENTS FOR MINIMUM INERTIA IN THE NORDIC POWER SYSTEM

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1. Background

1.1 European regulation

Article 39.3(a) in 'Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation' (EC 2017) requires that all transmission system operators (TSOs) shall conduct a common study per synchronous area to identify whether the minimum required inertia needs to be established, taking into account the costs and benefits as well as potential alternatives[1]. All TSOs shall notify their studies to their regulatory authorities. This report describes common Nordic studies, which justify that there is no need for defining the minimum inertia, as such, during the coming two years for the Nordic synchronous system.

This report explains which properties affect the frequency stability and how the Nordic TSOs ensure the stability. The report also describes that the instantaneous frequency minimum after a disturbance is an important criterion for maintaining the stability, and how the Nordic TSOs ensure that the instantaneous frequency minimum after the reference incident will not fall below the defined value, 49.0 Hz.

Several studies regarding the inertia and frequency dynamics are presented at a detailed level in the report 'Future System Inertia 2' (Ørum et al. 2017), prepared and published by Energinet, Fingrid, Svenska kraftnät, and Statnett, i.e. the Nordic TSOs responsible for the Nordic synchronous system. The Nordic TSOs will update the material through a collective study on inertia-related topics ending in 2026.

Furthermore, the Nordic TSOs have developed a model for transient frequency stability monitoring to be able to estimate the instantaneous frequency minimum in situations of large outages. The model can also be used to study frequency dynamics of the Nordic power system and to set requirements on frequency reserves. The model is used by applying a forecast of inertia and reference incident to forecast the instantaneous frequency minimum and necessary volumes of the Fast Frequency Reserve (FFR). The Nordic TSOs forecast inertia for the coming week to estimate the need of FFR.

Based on the above-mentioned model, the Nordic TSOs have developed technical requirements for the frequency containment reserves, FCR-N and FCR-D, to ensure frequency stability in a changing power system. There is currently an ongoing transition period of 5 years counting from 27. March 2023, where the providers will renew their prequalifications from the previous requirement to the current requirements. The shift is expected to happen continuously during the whole transition period. The current requirements for both FCR-N and FCR-D will affect the transient and small signal frequency stability. The study for a requirement for minimum inertia in the Nordic synchronous area is considered with a mix of the previous and the current requirements for the frequency containment reserves.

[1] *Article 39 is in the Appendix.*

1.2 Frequency requirements for the Nordic power system

1.2.1 Minimum frequency and automatic low frequency demand disconnection

In the Nordic synchronous system, the instantaneous frequency minimum shall be 49.0 Hz or higher after the reference incident, such as the trip of the largest power generating unit or an HVDC link importing power from a neighbouring system[2]. If the system fulfils this requirement, the frequency will be above 49.0 Hz after all other N−1 contingencies. The motivation for this frequency limit is that massive load shedding for maintaining the system stability will occur when the frequency decreases below 49.0 Hz (indiscriminative load shedding starts at 48.8 Hz).

The reference incident now and in the near future is the disconnection of the Oskarshamn 3 unit at maximum 1450 MW. The Olkiluoto 3 unit has a special system protection scheme, which automatically disconnects 300 MW load when Olkiluoto 3 trips. Therefore, the power imbalance after a disconnection of Olkiluoto 3 will be maximum 1300 MW and not 1600 MW.

1.2.2 System dynamics after a generator trip – the basic features

Figure 1 shows the dynamic response after disconnection of a generator with high and low inertia (high and low kinetic energy) in the system. For both cases, the amount of tripped active power and the volume of frequency reserves are identical.

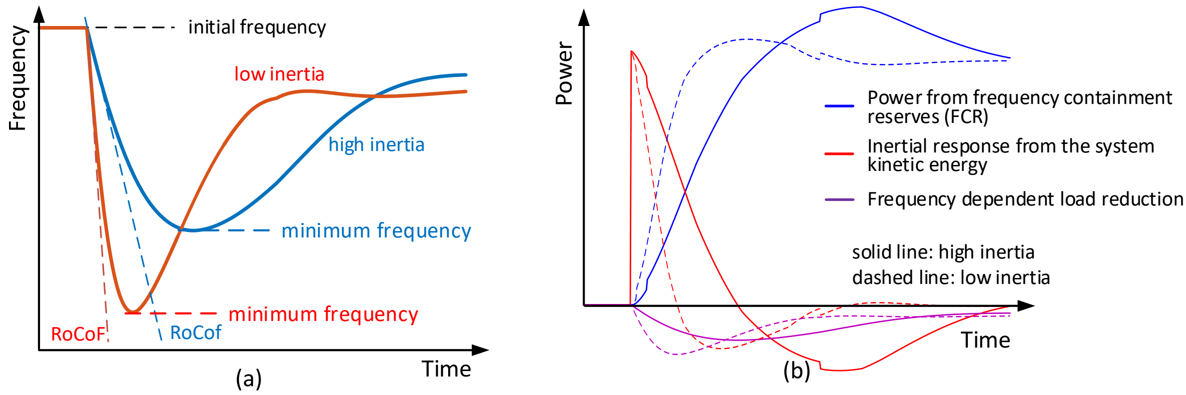

Figure 1. Frequency and power responses after a generator trip with high and low system inertia. A) Initial frequency and the frequency after a generator trip and the corresponding rate of change of frequency (RoCoF) values. B) Power responses from the kinetic energy (inertial response), from frequency containment reserves (FCR), and from the load reduction of the frequency dependent loads. The minor positive step in the power from frequency containment reserves comes from the HVDC FCR, which has an activation delay. (Statnett, Fingrid, Energinet, and Svenska kraftnät 2016 p. 35)

As Figure 1 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. Figure 1 also shows that the automatic reserves and the load reduction caused by the frequency dependency of the loads affect the frequency response. Tripping more active power leads to a larger frequency change if all the other factors remain the same.

[2] *SOGL art 18(1)(b)*

In the Nordic system, the frequency stability and maintaining the minimum frequency are critical. The rate of change of frequency is not a critical aspect after the reference incident since it is currently not high enough to cause generators to disconnect from the power system.

2. Maintaining the instantaneous frequency minimum above 49.0 Hz

2.1 Theoretical possibilities

As Figure 1 shows, the amount of system inertia and load dynamics affect the rate of change of frequency and the resulting instantaneous frequency minimum. The amount of tripped generation has an impact too. Reserves have an impact on the rate of change of frequency and the frequency nadir but this effect depends on how fast the reserves react. If the activation time is e.g. one second, the reserves affect the frequency change roughly after two seconds, not immediately after the disturbance.

The system inertia also affects the frequency in normal operation (for small variations in production and consumption) and hence the stability. The stability of the system decreases as the inertia decreases. The reserves must therefore also ensure a robust stability margin to secure sufficient dampening of the frequency in both transient and small signal phases. The stability of the frequency is paramount to have secure operation of the electricity system, both in outage situations and normal operation.

Three main factors (system inertia, tripped power, and reserve capability) define the frequency dynamics after a sudden power imbalance. The load dynamics also have an impact, but in practice it is difficult to control the dynamics and the amount of load. The system load and the load dynamics being out of control, the remaining possible methods for affecting the initial rate of change of frequency and the instantaneous frequency minimum are: 1) the system inertia, 2) the power imbalance, and 3) the response from the reserves.

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 (Ørum et al. 2017 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. (Ørum et al. 2017 p. 116)

The 'Future System Inertia 2' report identified several measures for mitigating the low inertia situations, fast frequency reserve (FFR) being one of them. The reduction of the reference incident, a measure already existing today, scores low in terms of cost and can be a "plan B". (Ørum et al. 2017 p. 117).

2.2 Fast frequency reserves

The Nordic TSOs procures FFR for the low inertia periods based on common technical requirements[3] . Tools and models to forecast needed FFR volumes and to monitor transient frequency stability were developed alongside national markets for procurement of FFR. Since the beginning of the FFR market in 2020 the liquidity has increased, and the Nordics see minor liquidity issues today.

The FFR procurement ensures that the system frequency will stay above 49.0 Hz during an N-1 incident, even in low inertia periods. The Nordic FFR demand includes a margin to cover for uncertainties in modelling and forecasting.

2.3 Limiting the reference incident

An option the TSOs 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 some nuclear generators may for example increase the risk of disconnecting the generator.

2.4 Simulated minimum instantaneous frequencies

Figure 2 shows simulation results on how the amount and parameters of FFRs affect the instantaneous frequency minimum after a power imbalance of 1450 MW in a situation when the Nordic power system post-disturbance kinetic energy is 100 GWs. The 100 GWs kinetic energy is considered a very low inertia situation, and it is used in simulations as a reference case. The figure indicates that it is possible to reach similar minimum instantaneous frequency with different FFR parameters (activation time and frequency).

Figure 2 shows that in addition to increasing fast frequency reserves, decreasing the reference incident (the amount of tripped generation) is a possibility of preventing too low instantaneous frequency values after a generator trip.

Figure 2 shows that adding the amount of frequency containment reserve for disturbances (FCR-D) by 600 MW is not sufficient for keeping the lowest instantaneous frequency above 49.0 Hz. The 'Future System Inertia 2' report explains that the Nordic FCR-D alone is not sufficient to guarantee that the instantaneous frequency minimum remains above 49.0 Hz at all times. (Ørum et al. 2017 p. 110).

The ability of FCR-D to reduce the instantaneous frequency minimum showed in Figure 2 is based on the average performance of the existing FCR-D delivering in accordance with the previous technical requirements.

[3] *Link to technical requirements on Svenska kraftnäts webpage*

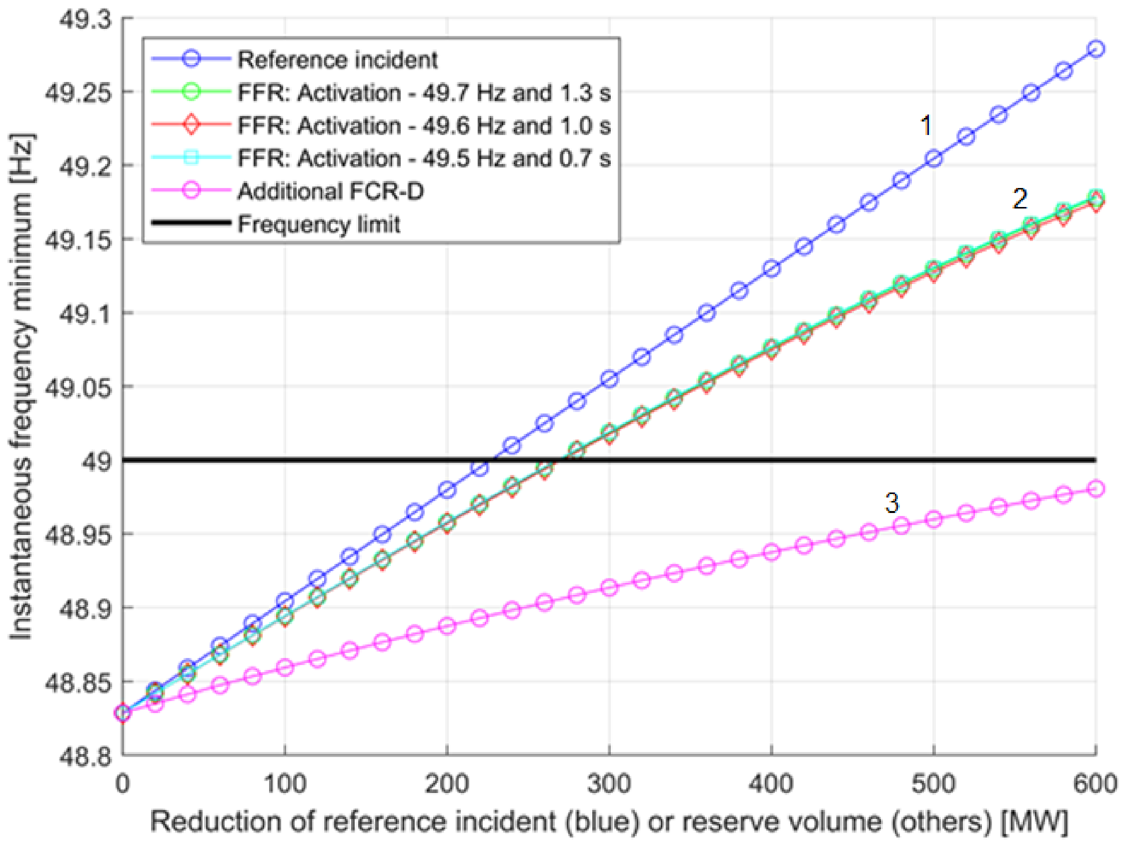

Figure 2. Simulated instantaneous frequency minimum values for the Nordic power system when the post-disturbance[4] kinetic energy is 100 GWs. The blue curve (1) shows the instantaneous frequency minimum after reference incidents (RI). The reduction of the reference incident $P_{red\text{-}RI}$ is calculated: $P_{red\text{-}RI}$ = 1450 MW – x, where x is the x-axis value (MW). The overlapping green, red and turquoise curves (2) show instantaneous frequency minimum values after a 1450 MW generator trip as a function of the volume of FFR (in the x-axis) with three different activation settings. The purple curve (3) shows the instantaneous frequency minimum values as a function of the volume of additional frequency containment reserves for disturbances (FCR-D) after the trip of 1450 MW.

2.4.1 Impact of current FCR requirements

The current requirements for FCR-N and FCR-D ensure sufficient stability and performance under the specified design levels for system kinetic energy (inertia). The design kinetic energy for performance for FCR-D is 150 GWs, which is the level where FCR-D keeps the frequency above 49.0 Hz during an outage of the dimensioning incident. The kinetic energy level for stability for FCR-D is chosen to be 120 GWs, which is the level where FCR-D ensures a robust stability margin and sufficient damping of frequency oscillations following large incidents.

For a system inertia below 120 GWs the stability margin of the system decreases. Hence, an increased oscillatory behaviour and reduced damping (higher settling time) of the frequency is expected. The current requirements for FCR-N and FCR-D ensure a robust margin at 120 GWs. It is therefore not critical that the system inertia decreases below this point. However, analyses show that the stability of the system is challenged around 90 GWs where other mitigation measures should be considered. The actual stability of

[4] *Post-disturbance kinetic energy is the kinetic energy value after the reference incident, i.e. the value without the tripped generator.*

the system will be dependent on different factors, especially the implementation of the current FCR-N and FCR-D requirements at unit level. The requirements are set to at a minimum ensure a sufficient margin based on a model of the Nordic system. Modelling uncertainties and better stability at unit level than required are the two biggest unknowns at the moment. Therefore, the Nordic TSOs will continuously monitor the frequency stability of the system and react if needed.

The chosen design kinetic energy levels should be as low as possible to ensure transient and small signal frequency stability in most operational scenarios, but still allow for enough capacity to qualify for FCR-D and FCR-N to achieve sufficient liquidity in the markets. The lower the design kinetic energies are, the harder the prequalification of the current requirements become.

For the chosen design kinetic energy for performance for FCR-D, 150 GWs, the need for FFR will most likely not change significantly and the FFR design is therefore feasible also for future low inertia situations.

3. Estimated inertia values for the Nordic synchronous area

3.1 Online kinetic energy estimation

The Nordic TSOs implemented a real-time kinetic energy estimation in their supervisory control and data acquisition (SCADA) and energy management system in 2015. The pre-fault kinetic energy values received from this online estimation system from year 2022-2024 are well above critical levels as shown in the following figure. If disconnection of a generator 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. The possible loss of kinetic energy from large incidents is in the order of 15 GWs in the Nordic power system.

Figure 3 shows the inertia of the years 2022 to 2024, where there is a clear difference between the seasons. During the summer the inertia is in average at the lowest level, however during winter the variation of inertia is the greatest. Some periods during winter/fall have a quite low inertia level, which is related to having a high share of renewable power production.

Figure 4 shows the duration curves for the years of 2022-2024. Year 2022 have the lowest variation of inertia, while year 2023 and 2024 in comparison both have higher and lower inertia levels. The lower inertia levels are partially related to having a larger share of renewable energy, combined with imports to the Nordic synchronous area over HVDC connections. One factor contributing to an increase in inertia in 2023 and 2024 is Olkiluoto 3 (nuclear plant in Finland) starting regular production in April 2023.

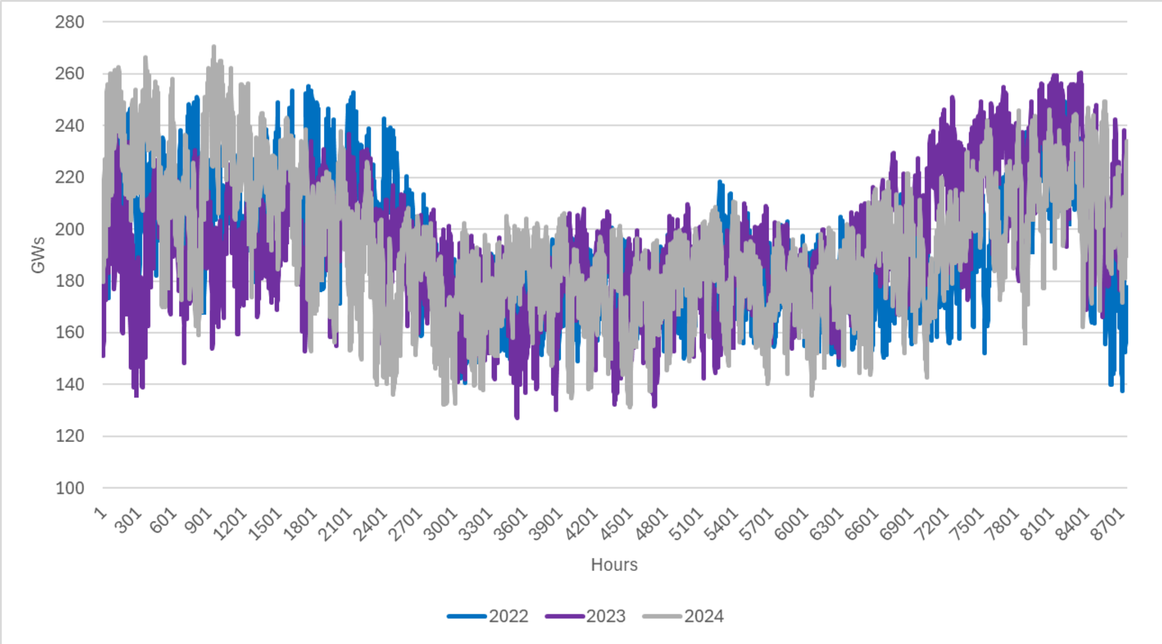

Figure 3. Estimated kinetic energy values (pre-disturbance values[5]) from the online kinetic energy estimation tool for the Nordic synchronous system in the years 2022-2024.

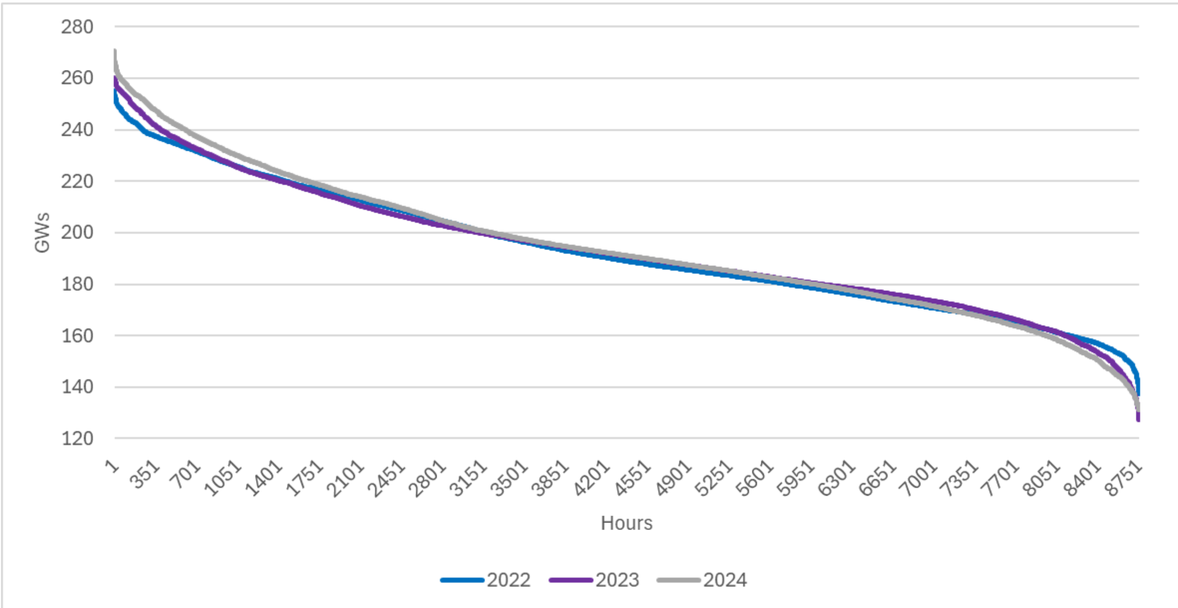

Figure 4. Estimated kinetic energy values (pre-disturbance values[6]) from the online kinetic energy estimation tool for the Nordic synchronous system in the years 2022-2024, as a time sorted curve.

[5] *Pre-disturbance kinetic energy is the kinetic energy value before the possible reference incident, i.e. the value with all the connected generators.*
[6] *Pre-disturbance kinetic energy is the kinetic energy value before the possible reference incident, i.e. the value with all the connected generators.*

Error! Reference source not found. presents key performance indicators (KPIs) for system inertia from 2022 to 2024, along with data from 2020 and 2021 as reported previously. A slight increase can be seen in the maximum inertia over the three years. The minimum inertia is slightly lower in 2023 and 2024, which can be reasoned by a higher renewable energy share, as explained above. The yearly average and standard deviation are quite close to each other.

The number of hours with inertia levels below 150 GWs increased significantly from 2022 to 2023, and again in 2024. In contrast, there were no recorded hours with inertia levels below 120 GWs during this period. This marks a notable change from 2021, when the system experienced 52 hours below 120 GWs. These figures suggest a trend toward lower inertia levels over time. However, the table and figures also show that overall inertia levels can vary from year to year, influenced by factors such as weather conditions.

	2020	2021	2022	2023	2024
Max (GWs)	256	256	255	260	270
Min (GWs)	135	110	138	127	131
Average (GWs)	190	195	193	194	194
Standard deviation (GWs)	25	31	24	25	27
Hours below 150 GWs	243	559	88	237	339
Hours below 120 GWs	0	52	0	0	0

Table 1. KPIs for inertia for 2022-2024, along with data from 2020 and 2021 as reported previously.

3.2 Estimating future kinetic energy

The Nordic TSOs periodically update long term inertia forecasts to proactively assess risks and consequences of very low inertia in the power system.

The estimation of future kinetic energy levels is shown in Figure 5 as duration curves for several different scenarios, with the x-axis showing the probability that there is at least that amount of inertia available. The duration curves show the year of 2035 and 2045. The following scenarios were used to generate the duration curves:

- SF is the small-scale renewables scenario, with the smallest growth in demand of the scenarios and decommissioning of nuclear but high potential for development and extension of renewables.
- FM is a mixed scenario that focuses on the potential to meet some increase of the demand with more renewables as well as lifetime extensions of existing nuclear and building new nuclear plants.
- EP is a scenario with a large increase in demand, as well as a growth in all energy sources, with a significance focus on the potential for extending lifetime of existing nuclear and building more nuclear plants.
- EF is also a scenario which has a large increase in demand, but a focus on a high potential for development and extension of renewables and nuclear decommissioning by 2045.

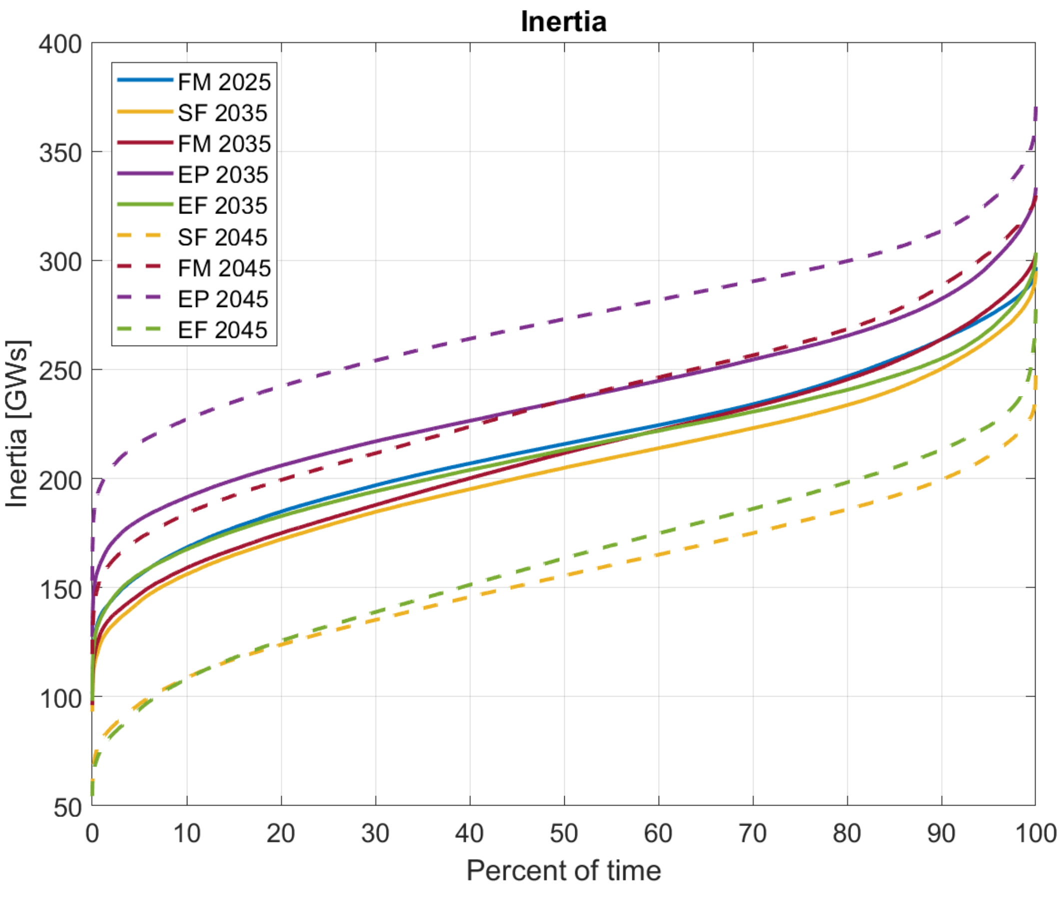

Figure 5. The kinetic energy pre-disturbance values (y-axis) and the corresponding probability (x-axis) in each scenario show the probability at which the system will have at least the amount of kinetic energy the curve shows.

4. Maintaining the frequency stability with fast frequency reserves

There is currently no need to define and require a minimum inertia (kinetic energy) value for the Nordic power system since other socio-economically efficient mitigation measures can be defined, like providing FFR or limiting the reference incident. The latter will be used only in exceptional situations.

As Figure 2 shows, with 100 GWs, roughly 300 MW FFR in the Nordic synchronous system is enough for maintaining the frequency stability with the performance of the previous FCR-D requirements and keeping the instantaneous frequency minimum above 49.0 Hz. This is based on a model, describing the frequency response, developed in the project 'Future System Inertia 2' (Ørum et al. 2017). In practise the FFR procurement is higher, as model and forecasting inaccuracies are considered by adding a margin. Figure 2 shows that even with different options for activation threshold and full activation time, all defined versions of FFR provide similar results. The different options give flexibility for the reserve service, and different technologies and providers will be able to provide FFR for the system. With lower kinetic energy values, the Nordic TSOs can ensure frequency stability by having higher volumes of FFR.

Furthermore, as market model simulations indicate lower inertia values in the future, further investigations of other measures than currently in use today are needed. One possible measure is to enhance the FFR product, to activate proportionally to the frequency deviation, which would be beneficial for the system and contribute to enhance stability. This service, referred to as dynamic FFR, and other possible mitigating measures when reaching lower inertia levels will be investigated in more depth in an upcoming Nordic inertia project.

The current requirements for FCR-D will increase the quality of the performance of the providing units regarding transient frequency stability. The actual implementation of the requirements at the reserve providing units will to some extent affect the needed volumes of FFR. However, the needed volumes of FFR are estimated to not change significantly compared to the volume with the previous requirements for FCR-D.

The current requirements for both FCR-N and FCR-D will also aid in ensuring small signal stability by introducing a system level stability margin through a corresponding stability requirement in prequalification testing. The stability margin will be crucial in situations of low inertia, and thus the current technical requirements for the FCR products are seen as an important aid in handling decreasing levels of inertia.

According to the feasibility study by the Nordic Analysis Group (Kuivaniemi, Jansson 2019), FFR is a more cost-efficient measure for handling low inertia challenges compared to reducing the size of reference incident. As an additional remedial action to FFR, limiting the reference incident can guarantee the frequency stability during exceptional situations.

5. Conclusion

Requiring a minimum inertia value is not needed for the Nordic system in the near future. Considering socio-economic aspects, feasibility and risks, it is efficient to use FFR as a complement to frequency containment reserves (FCR-D) to keep the instantaneous frequency above 49.0 Hz after a sudden power imbalance. As an additional remedial action to FFR, limiting the reference incident can guarantee the frequency stability during exceptional situations with low inertia.

Considering socio-economic aspects, feasibility, and risks, the current requirements for FCR-N and FCR-D will efficiently ensure transient and small signal frequency stability after sudden power imbalances and in normal operation. Likewise, as for maintaining the instantaneous frequency, it can be necessary to utilise remedial actions to guarantee the frequency stability during exceptional situations with low inertia.

Abbreviations

FFR	Fast frequency reserve is a system service that delivers a fast power change to mitigate the effect of reduced inertial response, so that frequency stability can be maintained.
FCR-D	Frequency containment reserve for disturbances.
FCR-N	Frequency containment reserve for normal operation.
HVDC	High voltage direct current.
RI	Reference incident means the maximum positive or negative power deviation occurring instantaneously between generation and demand in a synchronous area (EC 2017 p. 7). (Earlier the concept 'dimensioning incident' was used.)
RoCoF	Rate of change of frequency.
TSO	Transmission system operator.

References

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Appendix

Article 39

Dynamic stability management

1. Where the dynamic stability assessment indicates that there is a violation of stability limits, the TSOs in whose control area the violation has appeared shall design, prepare and activate remedial actions to keep the transmission system stable. Those remedial actions may involve SGUs.

2. Each TSO shall ensure that the fault clearing times for faults that may lead to wide area state transmission system instability are shorter than the critical fault clearing time calculated by the TSO in its dynamic stability assessment carried out in accordance with Article 38.

3. In relation to the requirements on minimum inertia which are relevant for frequency stability at the synchronous area level:
   a) all TSOs of that synchronous area shall conduct, not later than 2 years after entry into force of this Regulation, a common study per synchronous area to identify whether the minimum required inertia needs to be established, taking into account the costs and benefits as well as potential alternatives. All TSOs shall notify their studies to their regulatory authorities. All TSOs shall conduct a periodic review and shall update those studies every 2 years;
   b) where the studies referred to in point (a) demonstrate the need to define minimum required inertia, all TSOs from the concerned synchronous area shall jointly develop a methodology for the definition of minimum inertia required to maintain operational security and to prevent violation of stability limits. That methodology shall respect the principles of efficiency and proportionality, be developed within 6 months after the completion of the studies referred to in point (a) and shall be updated within 6 months after the studies are updated and become available; and
   c) each TSO shall deploy in real-time operation the minimum inertia in its own control area, according to the methodology defined and the results obtained in accordance with paragraph (b). (EC 2017)