European Network of
Transmission System Operators
for Electricity

Requirement for minimum inertia in the Nordic power system

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1. Background

1.1 European regulation

Article 39 (3a) 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 (TSO) 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.

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 Fast Frequency Reserve (FFR) volume needed. 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 new requirements for the frequency containment reserves, FCR-N and FCR-D, to ensure frequency stability in a changing power system. The draft requirements have been published for test in a pilot phase in the Nordics (Link to technical requirements on the Energinet web-page). The new requirements for both FCR-N and FCR-D will, when implemented, affect the transient and small signal frequency stability. The new requirements are expected to be implemented during a transition period from 2022 to 2027. Hence, the study for a requirement for minimum inertia in the Nordic synchronous area is considered for both the current and the new requirements for the frequency reserves.

1.2 Frequency requirements for the Nordic power system

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 protection scheme, which automatically disconnects 300 MW load when Olkiluoto 3 trips and therefore the power imbalance after a

[1] Article 39 is in the Appendix.

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

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disconnection of Olkiluoto 3 will be maximum 1300 MW and not 1600 MW. (Ørum et al. 2017, p. 107)

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.

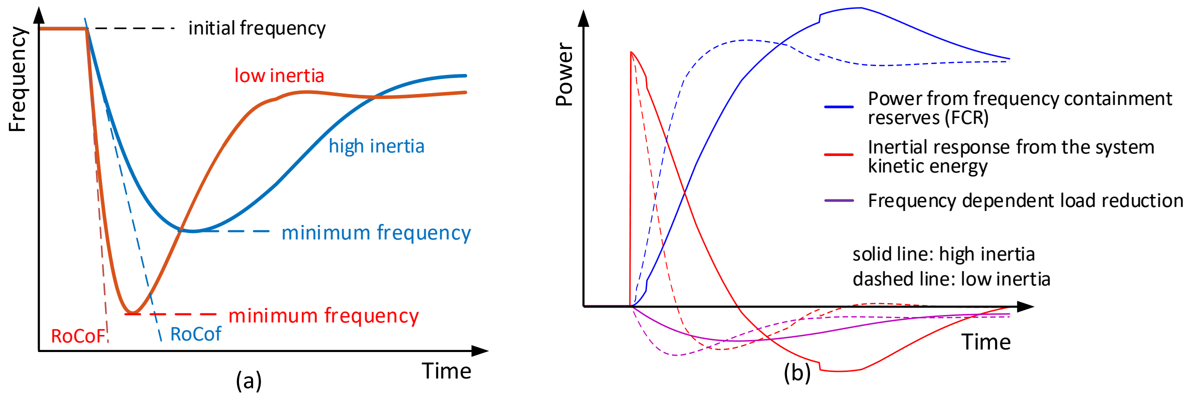

***Figure 1.** Frequency and power responses after a generator trip with high and low system inertia. a) Initial frequency and the frequency after a generator trip and the corresponding rate of change of frequency (RoCoF) values. b) Power responses from the kinetic energy (inertial response), from frequency 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.

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

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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 the TSOs cannot set requirements for the load 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

Promising mitigation measures, identified in the ‘Future System Inertia 2’ report is e.g. load reduction, which can be relay-connected load, converter-connected load, or high voltage direct current emergency power control (HVDC EPC) (Ørum et al. 2017 Section 8.3). These measures can provide FFR and are associated with low socio-economic costs. In addition, energy storage has proven to be able to provide FFR as well.

Since several technologies can provide FFR, the FFR parameters from different sources may be different. For example, the activation time can be instant (relay-connected load) or less than 0.5 seconds (converter-connected load, HVDC EPC) (Ørum et al. 2017 p. 93).

Experiences from 2020

The Nordic TSOs procured FFR for the low inertia periods of 2020 based on common technical requirements (Link to technical requirements on the Energinet web-page). Tools and models to forecast needed FFR volumes and to monitor transient frequency stability were developed alongside national markets for procurement of FFR. The liquidity on the national markets for FFR in 2020 differed. The market liquidity has increased for the FFR season in 2021, as the market is commonly known by providers and well established.

The frequency minimum following the reference incident is calculated in real-time based on procured volume of FFR, and data for system inertia and power of the reference incident. For a total of 6 minutes the Nordic demand for FFR was not met in 2020. During the FFR-season, there was never a risk of frequency decreasing below 49.0 Hz as the Nordic demand of FFR includes a margin to cover for uncertainties.

During 2020 more FFR capacity than needed was procured during approximately 1700 hours with a maximum of 149.3 MW of FFR for the Nordics due to forecast uncertainty and corresponding margins.

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Furthermore, FFR was activated according to the requirements in all countries in the only frequency disturbance in a low inertia situation where the first activation threshold of 49.7 Hz was reached on the 4th of June. The disturbance was well below the size of the reference incident, and hence the activation of FFR was not needed to meet the transient frequency targets. The trigger levels for FFR of 49.6 and 49.5 Hz was not reached for the same reason.

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 a nuclear generator 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).

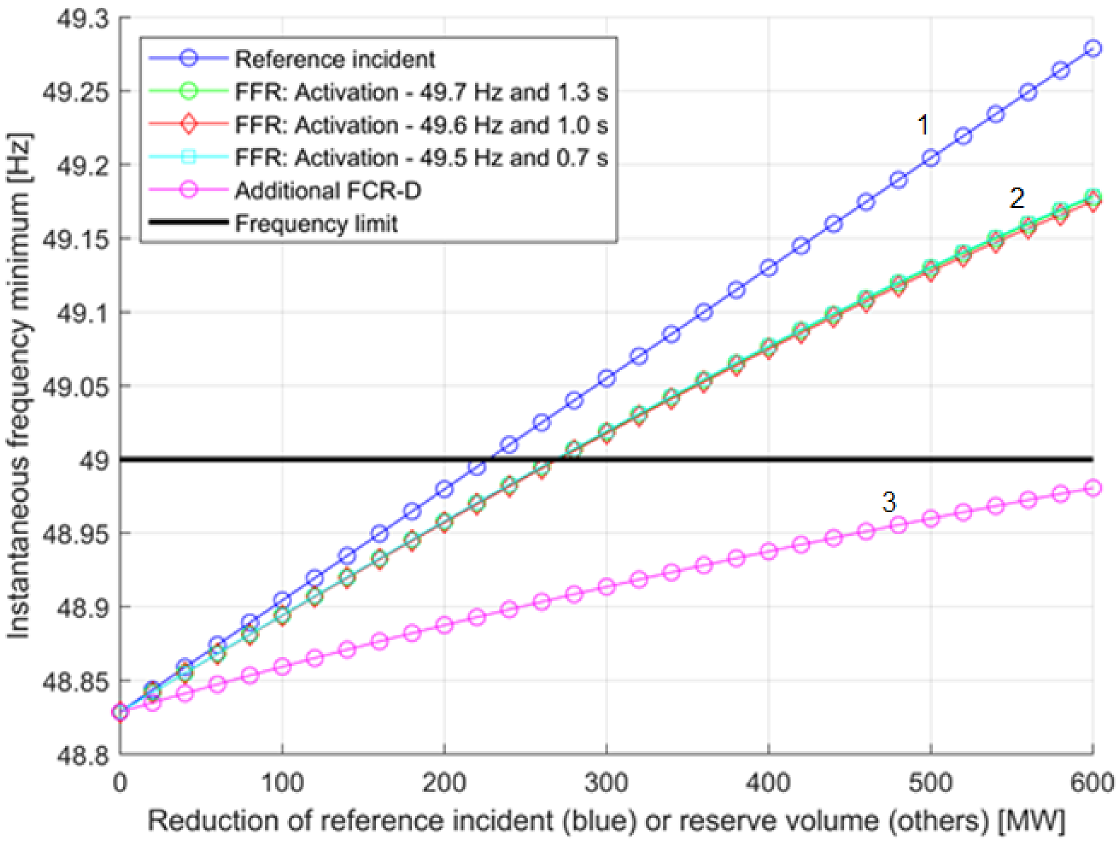

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Figure 2. *Simulated instantaneous frequency minimum values for the Nordic power system when the post-disturbance[3] kinetic energy is 100 GWs. The blue curve (1) shows the instantaneous frequency minimum after reference incidents (RI). The reduction 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.*

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 current 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.

Impact of new FCR requirements

New requirements for both FCR-N and FCR-D are under development. The new requirements will ensure sufficient stability and performance for both FCR-N and FCR-D under the specified circumstances based on the design levels for system kinetic energy (inertia).

Design kinetic energy for performance for FCR-D is the kinetic energy in the system for which the FCR-D keeps the frequency above 49.0 Hz for an outage of the dimensioning incident. The design kinetic energy for performance is based on thorough analysis to be 150 GWs.

Design kinetic energy for stability for FCR-D is the kinetic energy in the system for which FCR-D ensures a robust stability margin and hence sufficient damping of frequency oscillations following large incidents. Based on thorough analysis the design kinetic energy for stability is chosen to be 120 GWs.

For a system inertia below 120 GWs the stability margin of the system decreases. Hence, an increased oscillatory behaviour and reduced dampening (higher settling time) of the frequency is expected. The new 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 the system will be dependent on different factors, especially the implementation of the new 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 new requirements become.

This however, should be considered with the cost of procuring FFR during periods of lower kinetic energy than the one set for the design performance kinetic energy for FCR-D. Additionally, stability

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

challenges may arise if a very high need of FFR emerges in an exceptionally low inertia situations below 90 GWs. An activation of FFR following an incident that just reached the frequency activation thresholds of FFR at 49.7 Hz may cause frequency overshoots of equal magnitude.

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. Today, a need for FFR arises when the inertia decreases below 155 GWs (pre-disturbance, not including margins). Depending on the actual performance of FCR based on the new requirements for FCR it will reduce to 150 GWs or lower. The design kinetic energy for performance for FCR-D is the minimum requirement.

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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 2020 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.

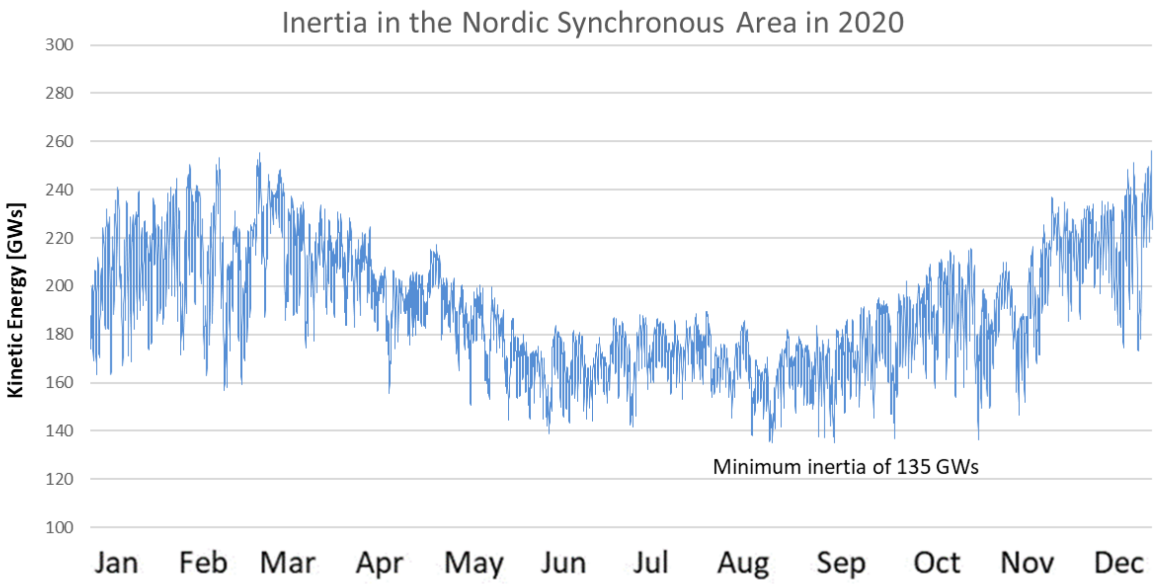

Figure 3. *Estimated kinetic energy values (pre-disturbance values[4]) from the online kinetic energy estimation tool for the Nordic synchronous system in the year 2020.*

3.2 Estimating future kinetic energy

Future inertia estimations for different future scenarios, presented in the 'Future System Inertia 2' report, show that with 99% probability, the kinetic energy will be more than 120 GWs or 134 GWs in 2020 and 2025, respectively. These values are presented in the two base case curves in Figure 4. The following duration curves show the future inertia estimates for different future scenarios (Ørum et al. 2017, p. 70 and p. 128).

The difference between the estimated kinetic energy in the synchronous area for 2020 from Figure 3 and Figure 4 is due to the weather. Figure 5 shows the variation in the forecasted kinetic energy in the Nordic synchronous area based on 31 input weather year data to the simulation model.

Currently, very dry and warm weather can shortly bring the kinetic energy level below 100 GWs in the current electricity system. This is for now unlikely, as stated above.

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

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The Nordic TSOs periodically update long term inertia forecasts to proactively assess consequences of very low inertia in the power system. Preliminary results of ongoing studies indicate that future inertia may decrease more rapidly than previously estimated.

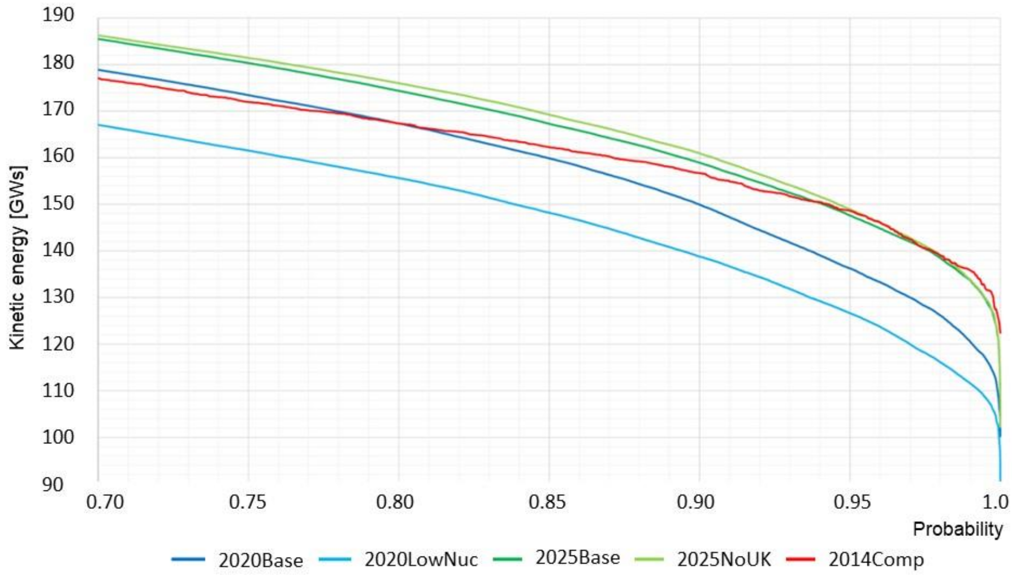

Figure 4. *The kinetic energy pre-disturbance values (y-axis) and the corresponding probability (x-axis) in each scenario show the probability at which the system will have at least the amount of kinetic energy the curve shows. The scenarios are for the year 2014 (2014Comp), 2020 (2020Base), 2025 (2025Base), 2020LowNuc (nuclear generation capacity in Sweden has been further decreased in scenario 2020 by shutting down two units in Ringhals) and 2025NoUK (a new 1400 MW HVDC link to the UK is postponed in the 2025 scenario). Note that the x-axis probabilities are between 0.7 and 1.0, which means that the highest kinetic energy values are not in the figure. (Ørum et al. 2017, p. 70)*

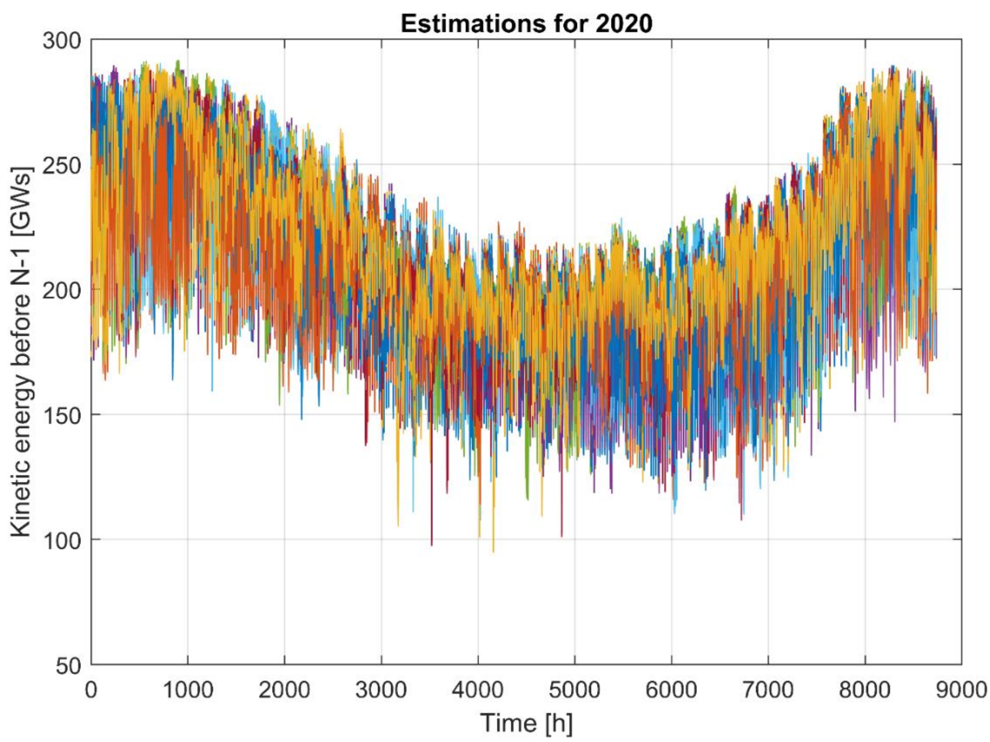

Figure 5. *The kinetic energy estimation for the base case of 2020 before the reference incident based on 31 input weather year data to the simulation model.*

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 only in exceptional situations.

As Figure 2 shows, with 100 GWs, roughly 300 MW FFRs in the Nordic synchronous system is enough for maintaining the frequency stability with the performance of the existing FCR-D 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). Figure 2 shows that with different activation frequency and full activation time, FFRs provide similar results. This gives 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.

The new requirements for FCR-D, which are expected to be implemented in 2022-2027, will increase the quality of the performance of the providing units regarding transient stability. The actual implementation of the requirements at the reserve providing units will affect the needed volumes of FFR. However, the needed volumes of FFR are estimated to not change significantly compared to the volume with the existing requirements for FCR-D.

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 with 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. For example, reducing the power of the largest generator connected to the system is possible, even though reducing nuclear generator output power may increase the risk of tripping the generator.

The new requirements for both FCR-N and FCR-D, which are expected to be implemented in 2022-2027, 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 new technical requirements for the FCR products that will be proposed by the Nordic TSOs are seen as an important aid in handling decreasing levels of inertia.

5. Conclusions

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 new requirements for FCR-N and FCR-D will efficiently ensure transient and small signal 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 and definitions

EPC	Emergency power control (of HVDC connections).
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.
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.

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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)

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