System Operations Committee / Regional Group Nordic

NAG - FREQUENCY QUALITY REPORT

Title	Final report
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Abstract

The purpose of this document is to describe the frequency quality challenges the Nordic Synchronous Area (NSA) faces and identify the factors and mechanisms that contributes to the frequency quality. By doing this, a next step can be taken to define frequency operational parameters that will ensure a sound and transparent frequency quality based on analysis and good operational practice. The report also investigates the impact on system operation as a result of various frequency quality levels.

The frequency quality trend of "minutes outside the band" has increased over the past years, indicating that the power system has been operated outside the original design parameters[1] and therefore the system security is subjected to increased risk. The time allowed outside the band per year ranges from 0.4 % to 5 % among the synchronous areas compared in this report. The current Nordic limit, 10 000 min/year, corresponds to 1.9 % of the time.

Changing the accepted minutes outside normal operating band has an impact on the probability of going below a certain lowest accepted frequency level during a Dimensioning Incident. A higher number of minutes outside normal operating band means a higher probability that the frequency is already under normal operating band when a major incident occurs, and consequently leads to a higher probability of going under a certain minimum instantaneous frequency. On the other hand, too strict target for number of minutes outside normal operating band may lead to unnecessarily high regulation costs.

Further work is recommended to be performed with focus on defining what acceptable risk the system can be operated with considering frequency quality level, and thereby finding reasonable limits for operation, both for normal state and disturbance state. The work shall also consider factors that today are known with a great deal of uncertainty, and that will be further affected by system changes the next coming years.

A folder containing the reference material is to be found in the ENTSO-E extranet under RGN/NAG and project name "Frequency Quality".

[1] Frequency Containment Reserves for Disturbance (FCR-D) is dimensioned such that the disturbance occurs when the system is within the normal band, however currently the frequency level during normal operation may be below 49.9 Hz more often.

Document

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Contents

List of abbreviations

ACE	Area Control Error
CPF	Cumulative Probability Factor
DC	Demand Connection
ENTSO-E	European network of transmission system operators for electricity
FALS	Frequency Activated Load Shedding
FANP	Frequency Activated Network Protection
FRR-A	Frequency Restoration Reserve- Automatic
FBF	Frequency Bias Factor
FCP	Frequency Containment Process
FCR-D	Frequency Restoration Reserve-Disturbed
FCR-N	Frequency Restoration Reserve-Normal
FRCE	Frequency Restoration Control Error
FRP	Frequency Restoration Process
HVDC	High Voltage Direct Current
LFC&R	Load-Frequency Control and Reserve, Network code
NAG	Nordic Analysis Group
NC	Network Code
NE	Northern Europe
NSA	Nordic Synchronous Area
NOIS	Nordic Operator Information System
PCP	Primary Control Process
PMU	Phasor Measurement Unit
RfG	Requirements for Generators
RGN	Regional Group Nordic
RAR	Review of Automatic Reserves
RKOM	Reglerkraftoptionsmarked (Regulating Power Option Market)
ROCOF	Rate-of-change-of-frequency
SCP	Secondary Control Process
SFR	Standard Frequency Range
SOA	System Operation Agreement
STD	Synchronous Time Deviation
TCP	Tertiary Control Process
TSO	Transmission System Operator

1. Purpose

This is a technical report delivered by the Frequency Quality sub-group of Nordic Analysis Group (NAG) to Regional Group Nordic (RGN). Its aim is to look closer at the historical and the present day's challenges of frequency quality in the Nordic Synchronous Area (NSA), as well as looking at the impact on system operation as a result of various frequency quality levels. This in order to create a basis for further work with defining operational limits for frequency. This will in the end ensure that the system in the future is reliable and operated with an appropriate level of system security. The report will also highlight certain factors that needs to be considered in order to be compliant with the forthcoming ENTSO-E Network Codes, foremost the NC LFC&R.

In the report, both normal operation and disturbance situations will be discussed, in addition to the overall technical challenges of frequency quality.

2. Introduction

Frequency quality is a measure of the power systems ability to maintain a stable operation during the changes of consumption and production that are creating imbalances; and to handle disturbances. The nominal frequency in the NSA is 50 Hz, with a normal operating band per today in the range of 49.9 to 50.1 Hz.

In the NC LFC&R [8], "Frequency Quality Defining Parameters" are to be found[2]. These ones include the following:

- Standard Frequency Range (often referred to "normal operating band" or "normal operating frequency band")
- Maximum Instantaneous Frequency Deviation
- Maximum Steady State Frequency Deviation
- Time to Restore Frequency
- Frequency Restoration Range
- Alert State Trigger Time

I.e. it is quite clear that frequency quality consist of more than one parameter. Further details for these parameters are to be found in Appendix A and relevant parameters are further discussed in Chapter 7.

In [7] report suggestions for new frequency quality indices has been proposed, which covers indices for identifying and quantifying frequency variations, as well as methods and principles for defining frequency events and possible measurement methods. The report describes present praxis for measurement techniques and what can be found within other synchronous areas. Were relevant, reference to [7] will be made when discussing new indices.

The frequency quality is mainly caused by insufficient balancing between production and consumption, and measured as "minutes outside the normal operating band".

Figure 1 shows that the trend of "minutes outside the band" has increased over the past years, indicating that the power system has been operated outside the original design parameters[3]

[2] The Network Codes referred to in this document are at the time being not implemented within the Nordic countries, and details within the codes have not been agreed upon by the Nordic TSO:s.

[3] Frequency Containment Reserves for Disturbance (FCR-D) are dimensioned such that the disturbance occurs when the system is at the limit of the normal band. However, currently the frequency level during normal operation may be below 49.9 Hz more often.

more often and therefore the system security is subjected to increased risk due to the fact that parts of the FCR-D is activated and thus not available if an actual incident would occur.

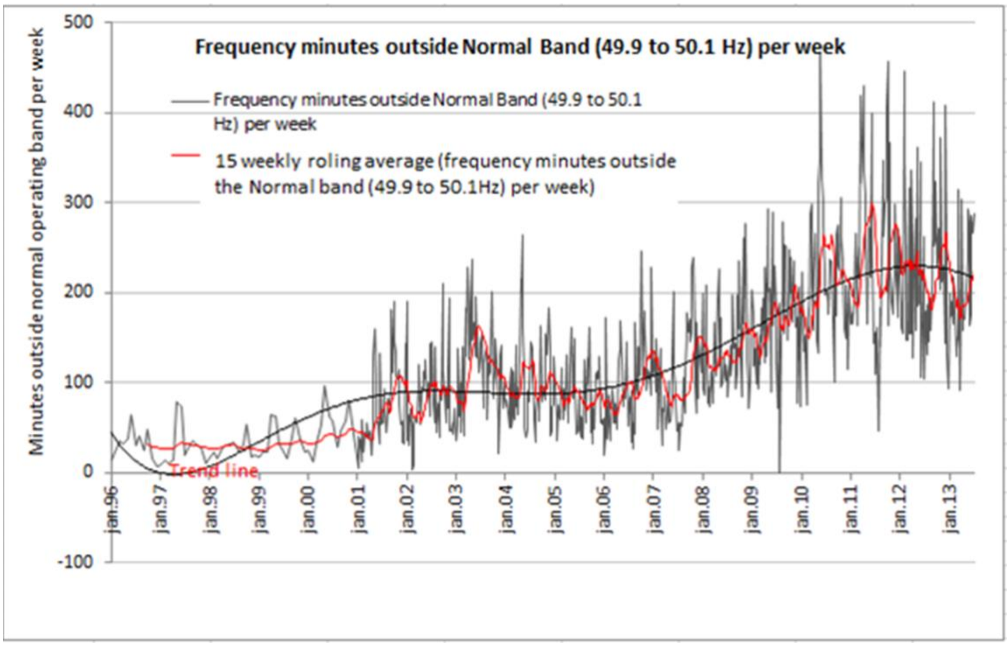

Figure 1 Frequency quality trend 1996-2013 based on weekly minutes outside the band. A change in data characteristics in January 2001 due to going from monthly to weekly average values.

Figure 2 further illustrates the trend in Figure 1. This figure shows a frequency plot from a 3 hour period in 1972 [35] and a plot of real frequency measurements of the same time and day from 2012. With a simplistic view, this can be one example of changes in frequency quality. It must however be kept in mind that all the different variables of the power system at the time of frequency recording was not known, neither the quality of measurement for the 1972 measurement.

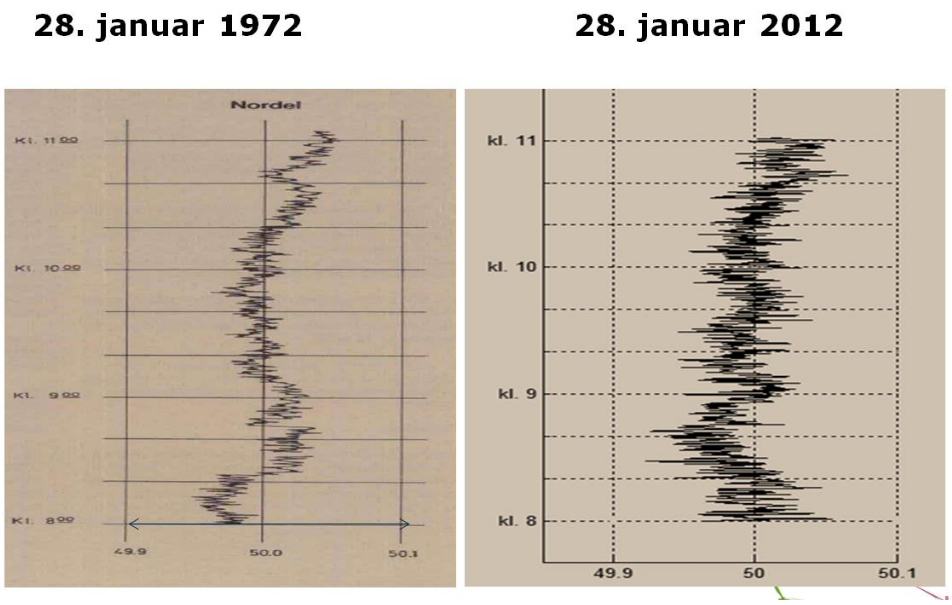

Figure 2 Oscillations have increased in 40 years ([35] and 2012 measurement values from ENDK Scada system)

The 2014 target for minutes outside the band has been defined in RGN to be 10 000 minutes/year (see section 4.1). In 2013 it was also 10 000 minutes/year. The performance year to date is shown below, also with reference to previous years.

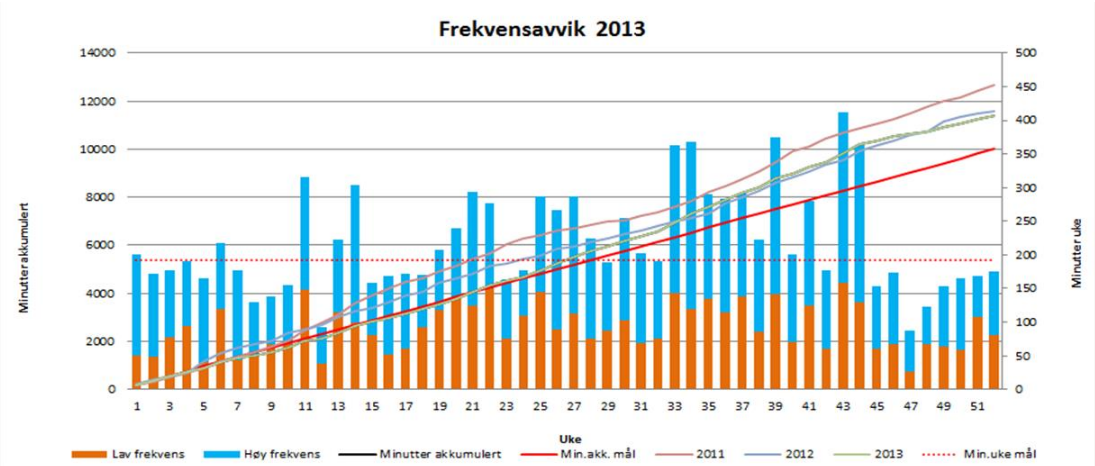

Figure 3 Frequency quality in 2013 – total minutes cumulative on the left and weekly bar on the right [from Statnett weekly report on frequency quality]

There are many possible reasons for the deterioration of the frequency quality in normal operation, significant factors include

- top of the hour imbalances due to market structure
- ramping of HVDC infeed from/to another synchronous areas

- increased amount of intermittent generation
- insufficient response time of manual balancing reserves
- increased frequency oscillations.

This is the fact even after introduction of quarterly movements (explained later) and better prognosis for consumption and wind power.

The resulting frequency after loss of large loads, production units or HVDC link serves as another indication of some aspects of frequency quality in disturbance situations, see Figure 4 for illustration. If such an incident takes place when the initial frequency is below the normal operating band some of FCR-D is used for balancing and is not available when the disturbance occurs. This can potentially result in load shedding or even blackout if the incident is severe enough[4].

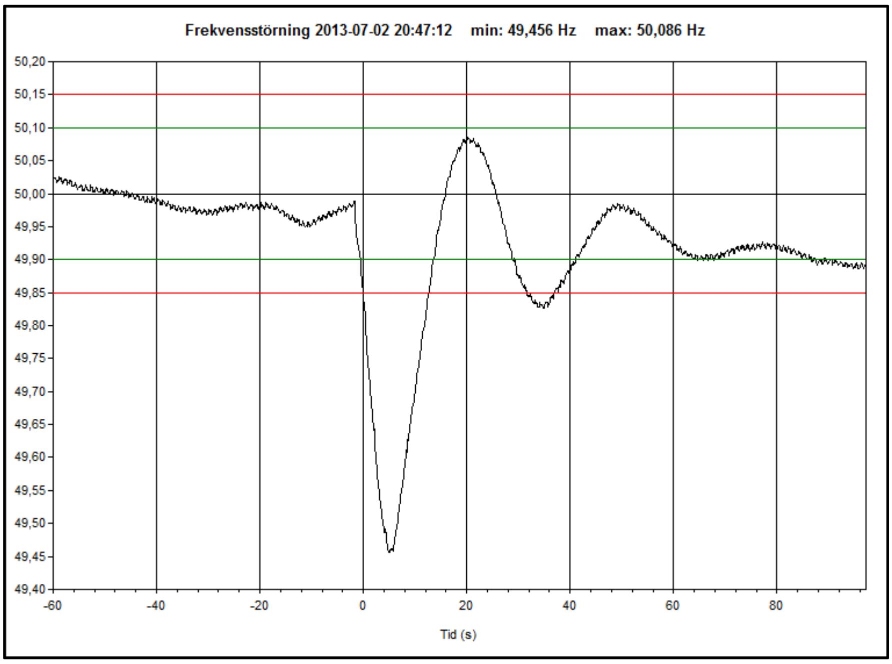

Figure 4 Typical frequency profile after forced outage of a large production unit (nuclear power plant).

A number of measures have been initiated to reduce the negative trend of frequency quality:

- Quarterly production plans
  The TSOs can quarterly adjust production in order to avoid large imbalances around top of the hour. This ancillary service allows the Nordic TSOs to move

[4] It should be noted that the potential risk of getting a system blackout as a result of a slight reduction of FCR-D should be seen as quite low. Blackout often requires multiple unforeseen events and more severe system conditions.

parts of the production up to 15 minutes ahead or postpone production up to 15 minutes[5].

- The ongoing NAG "60s project"[6] will find measures to reduce the oscillation (with period time of typically 60 s) in frequency.

- The Nordic TSOs have introduced automatic secondary reserves, FRR-A (Frequency Restoration Reserves- Automatic)

  FRR-A have a positive influence to the frequency quality as illustrated in figure below where the distribution of frequency for minutes outside the normal operating band is presented for different volumes during test period February to March 2013.

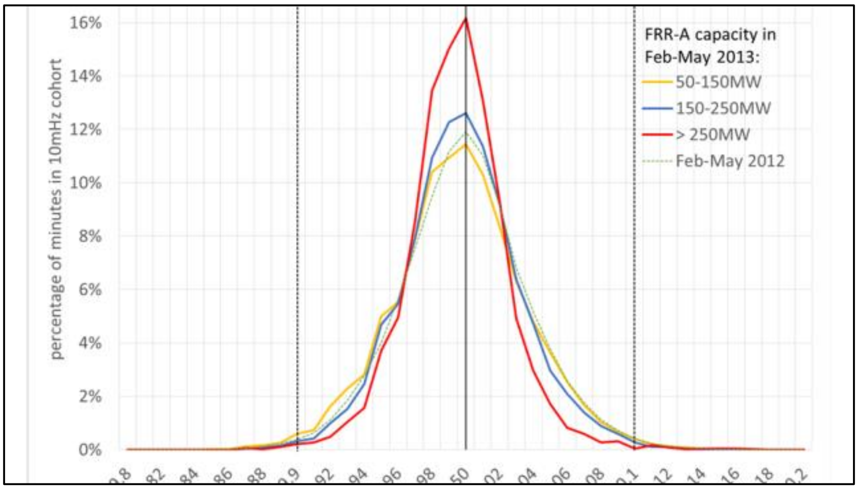

Figure 5 Distribution of frequency, separate for three levels of FRR-A during the test period from February to March 2013. [42]

The Nordic TSOs will have to comply with the Operational Network Codes (LFC&R [11], OS [26], OPS [33]) and connection codes (RfG [32], DC [29] and HVDC [34]) post 2016. Work is ongoing to develop a new System Operation Agreement (SOA) for the Nordic area. This report will indicate to RGN which parameters are to be included in the new SOA but will not recommend any values for them.

[5] https://www.entsoe.eu/news-events/announcements/announcements-archive/Pages/News/new-requirements-for-quarterly-production-plans-in-sweden-and-finland.aspx

[6] Project name is "Measures to mitigate the frequency oscillations with a period time of 60-90 s in the Nordic synchronous area". At the moment of writing, the 3rd phase of the project is to be started with the name "Revision of requirement for Nordic Frequency Containment Process".

3. Scope of work

The scope of work is to study operational and technical aspects in the Nordic synchronous system relating to frequency quality. The studies will be based on review of historic methodology, technology facts of 2014 and consideration to the new Network Codes obligations. Both the consequences of system stability in normal operation and in fault conditions (referred to as disturbance) will be considered. The consequences of different levels of frequency quality will be analysed and quantified.

The historical approach of the design of the Nordic power system will also be clarified where there are clear needs of this (historically accepted and agreed quality levels used today).

Frequency quality will be discussed in light of the comparison with other synchronous systems and the requirements of the LFC&R Network Code.

The following aspects are **not** included in the report

- Defining concrete levels for frequency quality levels like for instance normal operating band, minimum instantaneous frequency deviation etc.
- Defining/analyse frequency quality for island mode operation "or weak grid".
- Defining Dimensioning Incident (DI) in which amount of self regulating loads is a part.
- Frequency quality considering frequency oscillations.
- Analyse and describe possible indices/methods for identifying system disturbances (within the NAG activity "Future Inertia").

4. Frequency states

In the following chapter the definitions is given for the three different **frequency states**, as defined in NC OS (Network Code for Operational Security) [26] and in NC LFC&R [8]. The sub-states named "Normal operation/Operation outside normal operating band" are modes used in this report to highlight the difference between operation in Normal State, with or without an event.

- Normal State
    - Normal operation
    - Operation outside normal operating band
- Alert State
- Emergency State

Furthermore, the following is defined in the NC OS:

- **Disturbance** means an unplanned event that **may** cause the Transmission System to divert from Normal State

In the actual report, the definitions are used as follows:

- "Normal operation" will refer to Normal State without any event (disturbance or outage) and frequency within normal operating band.
- "Disturbance" will be used for outages with a resulting frequency outside the normal operating band (± 0.1 Hz). As seen in the definitions below, this event can result in operation either within "Normal State" or within "Alert State".

In this chapter, some definitions for island mode operation are also presented, even though this state is not referred to further on in the report (limitation of scope).

4.1 Normal State

According to the NC OS[7] [26], the system is in Normal State when

> ***Normal State*** *means the System State where the system is within Operational Security limits in the N-Situation*

N-Situation means the situation where no element of the Transmission System is unavailable due to a fault.

For the Normal State without disturbance (Normal operation), frequency quality indices that are related to the normal operating band can be defined. The NC LFC&R [8] defines the normal operating band as the Standard Frequency Range around the Nominal Frequency[8]. This Standard Frequency Range is ±100 mHz for the NSA.

The maximum annual number of minutes outside the Standard Frequency Range is set to a default 15000 minutes in the NC LFC&R [11] but the TSOs are allowed to agree on another value. The present limit for minutes outside normal operating band is 10 000 minutes (for 2014), set by RGN [30].

As defined in NC LFC&R Art 42 [11], the System Frequency limits for Normal State are fulfilled when:

a) the steady state System Frequency Deviation is within the Standard Frequency Range [*author note: +/- 100 mHz*]; or

b) the steady state System Frequency Deviation is not larger than 50 % of the Maximum Steady State Frequency Deviation [*author note: 50 % of 0,5 Hz, i.e. 0,25 Hz*] for a time period not longer than the Time to Restore Frequency [*author note: 15 min*]; or

c) the steady state System Frequency Deviation is not larger than the Maximum Steady State Frequency Deviation for a time period not longer than the Alert State Trigger Time [*author note: 5 min*].

See Figure 6.

Operation outside normal operating band includes outages when a significant loss of production, HVDC infeed or load disturbs the system by creating an imbalance. The Frequency Containment Process (FCP) means a process that aims at stabilizing the system frequency by compensating imbalances by means of appropriate reserves.

This process is common for the whole synchronous area, and a defined share of the reserves are allocated to individual TSOs.

The NC LFC&R [11] requires that the maximum contribution from a single provider of FCR should be limited to ensure that the consequences are kept to a minimum if a single provider would fail to deliver its FCR.

[8] Nominal Frequency means the rated value of the System Frequency (50 Hz in the Nordic synchronous area)

The NC LFC&R [8] defines the Dimensioning Incident (DI) as the highest expected instantaneously occurring active power imbalance within a LFC Block[9] in both positive or negative direction.

In operation outside normal operating band, these are the primary frequency criteria, as defined in NC LFC&R [8] and further illustrated in Figure 6:

- "Frequency Restoration Range" means the system frequency range to which the System Frequency is expected to return to after the Dimensioning Incident within the "Time to Restore Frequency". The default value in the NSA is defined in [8] to be ±100 mHz.
- "Maximum Steady State Frequency Deviation" means the maximum expected frequency deviation at which the system frequency is designed to be stabilized after the occurrence the Dimensioning Incident. The default value in the NSA is defined in [8] to be ± 0.5 Hz.
- The NC LFC&R [8] does not distinguish between FCR operating in the normal operating band (FCR-N) and that operating outside normal operating band (FCR-D). According to NC LFR&R, it is only in the NSA that two different products are specified, and in some cases with different specifications for speed of response.

4.2 Alert State

According to NC LFCR the following will result in Alert State

- The absolute value of the steady state System Frequency Deviation is larger than the Maximum Steady State Frequency Deviation; and
- the System Frequency limits for Normal State are not fulfilled

4.3 Emergency State

The Operational Security Code defines the Emergency State as the system state where

"Operational Security Limits are violated..."

The Operational Security Limits means the acceptable operating boundaries: thermal limits, voltage limits, short-circuit current limits, frequency and dynamic stability limits.

[9] Currently the Nordic synchronous system is managed as a single Control Block with common dimensioning of FRR and RR.

According to NC OS [26] the system enters emergency state in terms of frequency when the frequency goes below 49.0 Hz, has a steady state value below 49.5 Hz or is not restored to normal operating band in a time period less than or equal to the Time to Restore Frequency[10].

4.4 Island operation

Island operation is an operation mode that differs from region to region, depending of the possibilities they have. As these are very different no common rules or definition of frequency quality are being investigated in this report. Setting on generators may change when the operation covers only a minor area as an island[11].

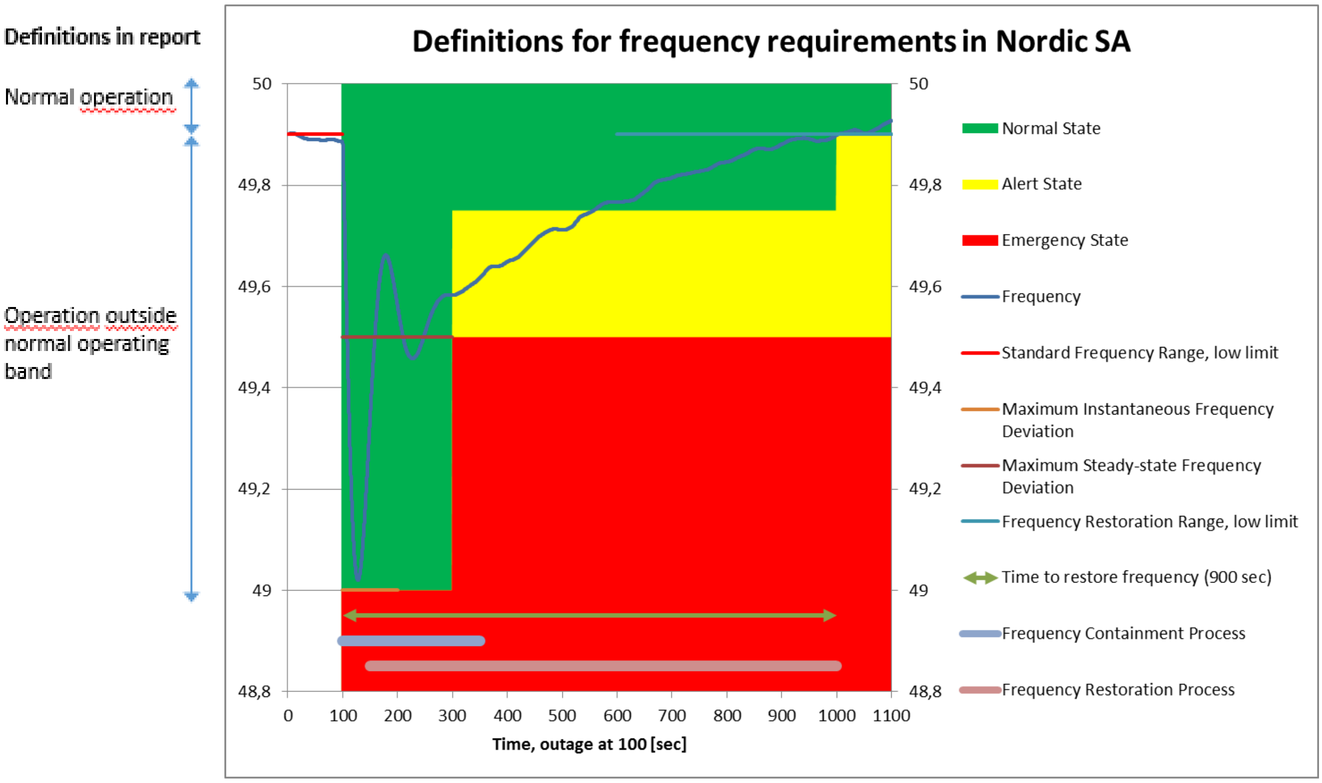

Figure 6 Definitions for frequency quality criteria, based on definitions in Article 42 in [8] and Article 8 in [26].

[10] There are some uncertainties within the project group how the limits for Emergency State shall be interpreted.

[11] During a winter storm in 2012, Norway was split to tens of separate islands.

5. Comparison with other synchronous systems

5.1 Introduction

A comparison of ten other synchronous systems, with nominal frequency of 50 and 60 Hz, has been undertaken. The key parameters are listed in Annex B. The reason for the comparison is to learn how other systems are managed in terms of frequency and system security. The key conclusions from this comparison are listed below.

5.2 Comparison in summary

The key parameters of nominal frequency, normal operating band, time deviation, frequency bias, quasi-steady state frequency and instantaneous frequency level have been compared. The nominal frequency is the same, 50 Hz, throughout all of Europe. Also most Asian countries and Australia use 50 Hz. Most parts of America use 60 Hz as nominal frequency. [6]

The normal operating band, how much the frequency is allowed to deviate during normal operation, varies between different synchronous areas. In the Nordic area the normal operating band is 49.9-50.1 Hz. In Continental Europe (former UCTE), Russia (including the Baltic countries) and US Eastern Interconnection the normal operating band is narrower; 49.95-50.05 Hz. In Great Britain, Chile and China the normal operating band is instead wider; 49.8-50.2 Hz, [6]. Australia has a normal operating band of 49.85-50.15 Hz [39].

There are different ways of characterising the normal variation of frequency. One way is to indicate the percentage of time or annual number of minutes outside the normal operating band. When comparing these figures it shall be kept in mind that normal operating bands are different in different synchronous areas.

The time allowed outside the normal operating band per year ranges from 0.4 % (Great Britain) to 5 % (Russia). The current Nordic limit, 10 000 min/year, corresponds to 1.9 % of the time.

Another way is to compare the allowed standard deviations of frequency. These values range from 0.026 Hz (Russia) to 0.092 Hz (Chile). The current Nordic target value of 10000 min/year outside normal operating band corresponds to the standard deviation of 0.042 Hz.

Regarding allowed time deviation; ± 30 s is used in the Nordic area, Continental Europe, Great Britain and Russia. Australia has specified a value ± 5 s for the mainland and ± 15 s for Tasmania, [39]. Western USA uses an even shorter value, ± 2 s [43].

The method to correct the time deviation differs. In the NSA the time correction is mainly done manually. However the Nordic FRR Technical Group has proposed to manage this automatically as is the practice in Russia [6]. The NC LFC&R [8] does not require the definition of target value for time deviation for the Nordic area.

The frequency bias factor (FBF), [MW/Hz], also known as the primary control frequency response, is mainly provided from FCR. The FBF gives the remaining frequency deviation after a system disturbance, i.e. it represents the "stiffness" of the system. The frequency bias factors are not directly comparable as the system sizes are different in the terms of generation capacity. The requirement for minimum frequency bias factor provided from reserves is 27 GW/Hz in the US Eastern connection, 15 GW/Hz in Continental Europe and 6 GW/Hz in the NSA. The frequency bias factor is in practice higher, typically 29 GW/Hz in Continental Europe[12] and 8 GW/Hz in NSA [36] (including the frequency dependence of loads). The higher this value is the smaller will the frequency change be after an incident causing power imbalance. If for instance a 1000 MW unit trips the steady state frequency change will be 40 mHz in CE and 100 mHz in NE.

In the NSA it is required that 50 % of FCR-D is activated in 5 s and the rest in 30 s, whereas the activation time of FCR-N is longer, 2-3 min. In Great Britain it is required that all FCR shall be activated within 10 s[13] [6]. In Continental Europe and in Russia the activation time of FCR is 30 s.

The minimum instantaneous frequency for the NSA is not specified in the current System Operational Agreement but older reports state 49.0 Hz [52], [17]. This is also set in the NC LFC&R [8] as a default value, and the Nordic TSOs are allowed to agree on another value. Continental Europe [40], Great Britain and Russia use the minimum frequency 49.2 Hz [47].

The quasi steady state frequency, the level the frequency should at least have reached within 30 - 60 s after a disturbance, is 49.5 Hz in the NSA and in Great Britain, whereas in Continental Europe and Russia it is set to 49.8 (50.2) Hz [6].

5.3 Key conclusions

Key conclusion from the comparison are:

- **Normal operating band** - varies between ± 50 mHz and ± 200 mHz. The Nordic definition is ± 100 mHz.

[12] This value has been calculated in CE WG SF from 90 outages (Erik Ørum is a member of this group)

[13] GB has more types of FCR, where one part has a fast response in 10 sec with limited duration – 30 sec, the second type has a response in 30 sec with limited duration – 30 min [44]

- **Time allowed outside the normal operating band** – ranges from 0.8 % to 5 % of the time. The NSA current performance is 1.9 %. **The standard deviation of frequency** - ranges from 0.026 to 0.092 Hz. The NSA current performance is 0.042 Hz[14].
- **Allowed time deviation** – The Nordic limit of ± 30 s is consistent with several other systems, even though also smaller values are also used in Western USA and Australia. NC LFC&R however do not require this value to be specified any more in the Nordic area
- **Frequency bias factor** – this relates to the accepted drop in frequency after stabilizing. The minimum requirement is 6 GW/Hz for normal operating band for NSA and 15 GW/Hz for Continental Europe. The performance is in practice better compared with the minimum requirements.

  The frequency bias factors are not directly comparable due to differences in system size and system needs.
- **FCR activation time** – The fastest response is found in Great Britain 100 % in 10 s, Continental Europe is 30 s and Nordic is 50 % in 5 sec and 100 % in 30 s.
- **Minimum instantaneous frequency** – this is not specified in the current System Operational Agreement but older reports state 49.0 Hz. The value is 49.2 Hz in Continental Europe, Great Britain and Russia.
- **The steady state minimum frequency** – this is 49.5 Hz in the Nordic area and in Great Britain and 49.8 Hz in Continental Europe and Russia.

[14] 10 000 minutes outside normal operating band corresponds roughly to standard deviation 0.043 Hz.

6. Background of frequency containment process

6.1 Introduction

A survey regarding the history of frequency quality and design of the frequency containment process (FCP) has been done in order to clarify why the NSA normal operating band and Frequency Containment Process (FCP) is designed as it is.

In order to make this survey, four interviews and a workshop have been arranged. The interviewed have helped us in an educational and engaged way and contributed with material from decades regarding the NSA history of frequency quality.

We would like to thank Sture Lindahl, Sture Larsson, Kenneth Walve, Set Persson, Jørgen Falck Christensen and Ole Gjerde for their contribution in order to make this survey.

6.2 Electricity market development

As the Nordic electricity market developed and the demand for electricity grew during the 60s, 70s and 80s the electricity companies tried to prognosticate the development of electrical consumption in order to build power new power plants in time. These prognoses took into account the risk for a possible electricity shortage and what national economic consequences a shortage would imply. In 1982, Svenska Fysikersamfundet concluded that an acceptable rate of occurrence of electricity rationing was once every thirty year. [49]

The Nordic electricity market was deregulated in 2000. Before the deregulation, the electricity companies were producers, consumers and system operators. To create incentives to exchange energy between companies a bilateral trade's price was settled between the two trading companies marginal prices. This bilateral market of electrical energy was used until the deregulation of the Nordic electricity market. This deregulation started in Norway by a parliament's decision in 1991 but the market was not fully integrated until Denmark joined in the year of 2000. [50] [49]

The deregulated market is an energy market per hour. As the need for electrical consumption changes within the hours but the production companies start and stop production at top of the hour the new deregulated market has created problems with keeping the frequency within the frequency bandwidth at top of the hour.

A condition for being able to exchange electricity between companies freely with only variable cost as marginal prices is that delivery dependability exists. Before the deregulation all companies accepted a joint delivery dependability agreement to make it economic efficient. Today the market with help by the transmission system operators creates incentives to keep a delivery dependency. [49]

The tariffs for the FCR have also changed. Before the deregulation special tariffs were applied to the nuclear power plants to cover the costs for FCR-D and there where demands for every producer to contribute with FCR-N in relation to their production. Today the TSO has created different markets to minimize the costs for these reserves. This cost is then paid for by different national tariffs. [51][23]

To balance the production and consumption the Norwegian and Swedish TSOs have a shared responsibility. Balancing based on the national imbalances was done nationally, before the common Nordic balancing market was established in year 2002. The balancing was done using ACE calculations, $\Delta P + K_i * \Delta f$ where K_i is the relative share of frequency controlled normal reserves [48]. The activation was a manual process and the used reserves was from within each country.

When the common market was introduced, this also implied that activations of resources could be shared. This meant that if DK needed to up-regulate, DK could ask SE to up-regulate instead, if they had lower activations prices. Thru this SE could have both up and down regulation – which was non-optimal. This was solved by giving NO and SE a joint responsibility for activation of reserves (also in DK and FI) – via calls to these two TSOs. Through this change of responsibility, the use of ACE disappeared and the balancing was performed based on the sum of all national imbalances.

Before the deregulation, Statkraft and Vattenfall had a responsibility to restore FCR. A belief is that it was not as hard as today to keep the frequency within the bandwidth limits as there were progressive fees for imbalances which made the integrated companies, covering both production and consumption, to hold there electrical balances better. These integrated companies were, due to the deregulation, split into production, consumption companies and the transmission system operators.

6.3 Background of frequency quality requirements

The Nordic power system has been designed with the goal of keeping frequency within the range of 50 ± 0.1 Hz. The assumption that the frequency is normally inside this range has affected the design of the power system. Because of this, the time the frequency is within the range 50 ± 0.1 Hz is one central aspect of frequency quality. [11]

Consumers and producers of electricity and transmission grid operators have different perspectives to frequency quality. From the consumer's perspective, the current frequency quality is good enough. Some industries, such as mechanical paper industries can be sensitive to fast rate of change of frequency, but for the rather large Nordic power system this is not a problem. If however operational security of the power system is reduced due to poor frequency quality this will have an economic impact on the industry. [15] [12] [18]

The frequency quality is more important from a producer's perspective. If a production unit is used for frequency regulation, the frequency variations cause more regulation and consequently more wear of the unit. High and low frequencies are a problem also for thermal power plants. They are able to operate for only a limited time at frequencies outside the range 49...50.3 Hz and there is a risk of vibrations in turbine shafts at frequencies outside this range. [12] [13]

A transmission system operator perspective focuses on operational security: Keeping the boundaries established for normal frequency aims at having the FCR-D disposable for activation when a disturbance occurs. A well-founded design with a functional interaction between frequency containment reserves and load shedding contributes to a reliable and robust power system.

Frequency boundaries 50 ± 0.1 Hz

Kungl. Vattenfallstyrelsen wrote in 1957 that with the introduction of electrohydraulic governors it was not a problem anymore to maintain the frequency within the frequency boundary 50 ± 0.1 Hz. The decision to use 50 ± 0.1 Hz as the normal interval has been up for discussions but the main reason of having a strict interval is to minimize the risk of having frequencies above 50.3 Hz after trips of load. If the frequency is above 50.3 Hz the thermal power shafts can start to vibrate, which increases the units wear. Another advantage with using ± 0.1 Hz instead of ± 0.2 Hz as boundary is to give the FCR-D an extra second to respond to a disturbance if the frequency is low at the instance of the disturbance. [19] [12] [15] [13].

Still another reason for defining the range 50 ± 0.1 Hz in normal operation was to operate close to highest point of efficiency, i.e. close to nominal frequency[15].

Lowest instantaneous & steady state frequency

During the late 1900s, the power system FCR-D has been designed to keep the minimum instantaneous frequency at or above 49.0 Hz after a Dimensioning Incident and raise the steady state frequency above 49.5 Hz within 30 s after the disturbance. [12] [20] [17]

Definitions of the instantaneous and steady state frequencies are illustrated by simulated curves in Figure 7.

[15] This is also for the operation per today, but there is also an additional general total income optimization that might in some cases give a positive outcome operating at wider frequency levels.

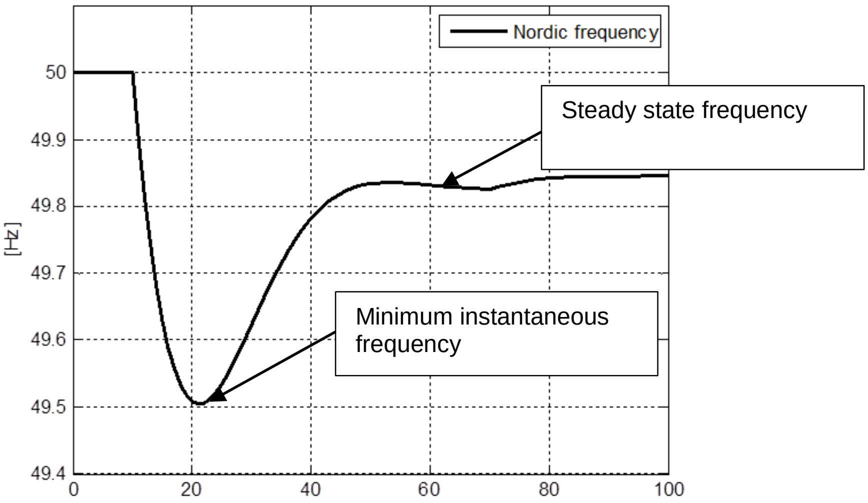

Figure 7 Simulated frequency development when a disturbance occurs. Simulation model from [36] used.

6.4 Frequency Containment Process (FCP)

In an electric power system there is all the time a balance of electric power. A disturbance (a loss of generator, load or HVDC-link or just a stochastic difference in production and consumption) does not cause a power imbalance but only a change in how the balance is maintained. During frequency deviations the electrical balance is maintained by the decrease or increase of the kinetic energy of the turbines and generators. The frequency containment reserves interrupts the frequency alterations and in so doing the withdrawal/storage of power from the stored kinetic energy. [11] [24]

FCR-N

The current regulation method of FCR-N was developed during the 20th century. Instead of letting a few main power plants do the regulation it is distributed to several power plants. The FCR-N is delivered mostly by hydropower plants.

FCR-D

Frequency dependent disturbance reserve (FCR-D) has been designed to keep the frequency above the minimum instantaneous frequency after any N-1-incident. The minimum instantaneous frequency should in turn be above frequency levels at which automatic load shedding starts. If part of the FCR-D is not available when the disturbance occurs this can lead to load shedding. If the load shedding fails to bring the frequency to levels where power plants can stay in operation some power plants will be tripped, which can lead to lower and lower frequencies due to more trips of generating units and ultimately to black-out. Operational limits for power plants are visualized in Annex D – Automatic Load shedding schemes.

There was a review of the Nordic FCR–D and the automatic load shedding design during the 1970 because of the installation of large nuclear power plants. The FCR-D consists mostly of power from hydro power plants. Some of the FCR-D is also delivered from HVDC frequency support, thermal power plants, hydropower in synchronous condenser mode and disconnection of loads. [14] [22] [12] [21] [23]

To restore FCR

To restore FCR the start up time of the manual Frequency Restoration Reserve (FRR-M) has been set to 15 minutes. One of two main reasons for having a time limit of 15 minutes is that it is a good time span for starting up hydro power units and gas turbines. The second reason for it is the fact that it takes approximately 15 minutes for an overloaded power line to start sagging dangerously[16]. [51]

6.5 HVDC emergency support

HVDC emergency support is activated at frequencies between 49.9-49.0 Hz and 50.3 – 51.0 Hz. Some emergency support should be seen as FCR-D and some just as emergency support, but the difference between the two "products" is not clear as seen in Figure 8 and system protection layout in [53].

The only HVDC emergency support that can always be counted on is the FCR-D from HVDC connections which is 50 MW from KonTek and 18 MW from Storebælt when these HVDC-links are in use.

[16] Rule of thumb. Depends on loading before over loading occurs, and is also depending on chosen construction criteria of single lines.

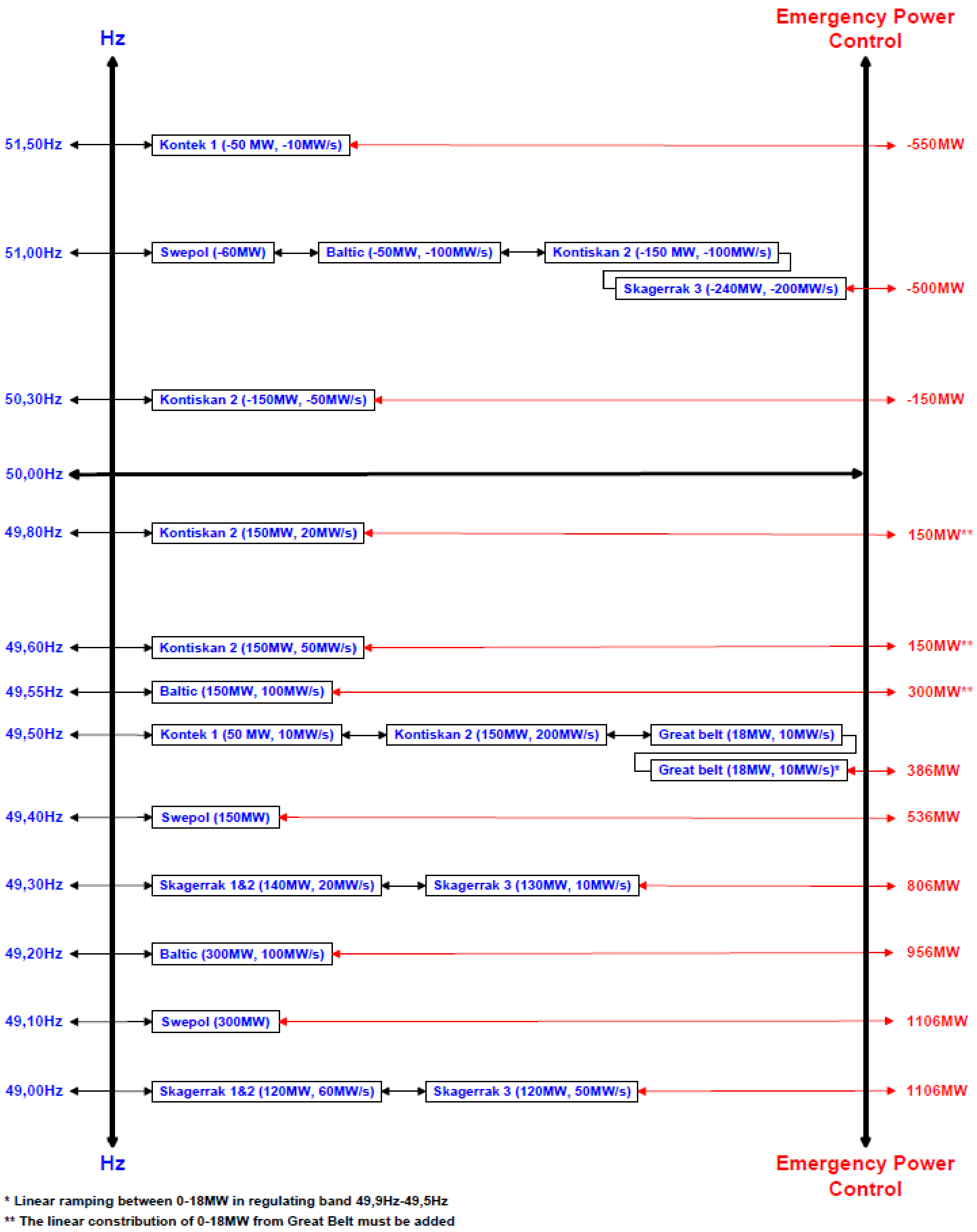

Figure 8 HVDC emergency support in the NSA.

6.6 Automatic Load Shedding

It has become standard in power systems to use automatic load shedding to avoid low frequencies that can trigger power plants protection relays. The main reason for avoiding this is that a power plant trip due to low frequency will most likely lead to blackouts. [16]

The concept Frequency Activated Network Protection (FANP) was introduced in the 1980s. The concept means automatic, decentralized load shedding that does not cause disconnection of ordinary consumers' load. The region where ordinary consumers were disconnected was called Frequency Activated Load Shedding (FALS). Figure 9 gives the structure of the frequency activations from 1983, and in Annex D – Automatic Load shedding schemes from today, with details for each country within the NSA, is specified.

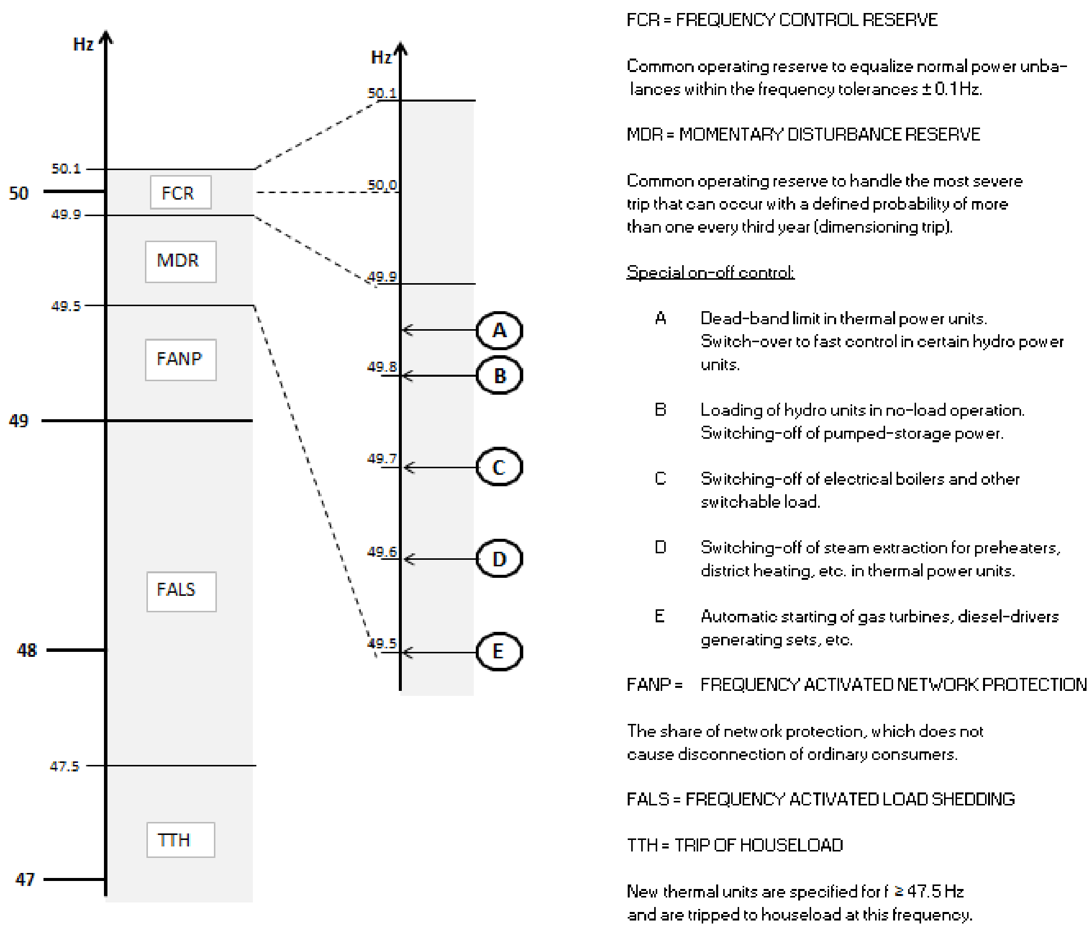

Figure 9 Frequency activation regions for various system services activated by instantaneous frequencies [17]

6.7 Aspects affecting the design of FCR

One aspect is the **frequency oscillation.** Today there is a frequency oscillation in the Nordic power system with a time period of around 40-90 s. It is not yet fully clear what the causes of the oscillation are, but it is amplified by the FCR-N response which have a resonance peak around these frequencies. Higher amplitude of the frequency oscillation implies an increased need of FCR-N to reach the same frequency quality goals (provided that the FCR doesn't excite the oscillations). It seems unlikely that there is a way to completely eliminate the 40-90 s oscillations. So they will continue to contribute to the minutes outside normal operating band and consequently affect the need for FCR-N. [25] [13] [12]

Another aspect that affects the need of FCR-N is the **load variations**. Disregarding the market problem at top of the hour with changes of power production, several studies have been performed to assess how much load varies. Studies done in the 1970s concluded that the load variations could be up to ± 1 % during a few minutes. It is recommended that these variations are taken into account when dimensioning the FCR-N and if the variations increase the need of FCR-N increases [13].

The measurements will need to be improved to facilitate the monitoring of load variation. Currently it is only possible to estimate the variation of imbalance in the NSA by measuring the frequency variation and converting that to imbalance variation based on assumed (not calculated or measured) of frequency bias factor. At least power measurements of all significant generators and perhaps also of loads with sufficiently high time-resolution are needed but are not yet sufficiently available to the TSOs.

The power system's **kinetic energy** is stored in the rotating mass of the power systems generators and turbines that are synchronously connected to the grid. When frequency changes the rotational speed of the generators also change. When the frequency increases, energy is stored when accelerating the generators and turbines. When the frequency decreases energy is supplied as the speed of the rotating mass decreases. If the stored kinetic energy decreases the need for speed of FCR response increases. [11] [13]

During a disturbance the **frequency and voltage dependence of loads** affects the lowest instantaneous frequency and the steady state frequency after the disturbance. During disturbances, the frequency changes gradually in the whole system, whereas the voltage changes instantaneously but locally. Therefore gradual changes of loads caused by their frequency dependence take place in the whole system, while instantaneous changes of loads caused by their voltage dependence occur mainly in certain areas. When dimensioning the FCR-D a fixed reduction of load (200 MW) is assumed when the frequency drops to the lowest acceptable steady state value of 49.5 Hz. The voltage dependence of loads is not taken into account and is also difficult to take into account since it depends on where the trip of power takes place and in which way the tripped unit contributed to the power flow in the system before tripping. [13] [12]

6.8 Designing FCR

If the problems at top of the hour and the frequency oscillations are disregarded, the amount of FCR-N needed can be approximated. With the frequency bandwidth of 0.1 Hz, the historic assumption that the load vary with ± 1 percent and the fact that the maximum load in the NSA is around 60 000 MW the need of **FCR-N** is approximated to 600 MW. [12] [13] [15]

This amount of FCR-N needed is also affected by how well organized the operation monitoring is. For example, it depends on how well the producers and consumers follow their production and consumption plans (it should be noted that even though plans are followed on hourly basis, deviations from plans can occur on shorter time periods with resulting impact on the frequency quality). This information could be helpful when making a decision of the amount of secondary regulation that is needed. Also, if the secondary regulation takes five or fifteen minutes to restore the FCR-N or whether it is automatic or not will also affect the amount of FCR-N needed. In the end, the amount of FCR-N has been decided by considering the cost of achieving an acceptable frequency quality level.

When designing the **FCR-D** it is assumed that the frequency, when the disturbance occurs, is above 49.9 Hz. The Dimensioning Incident (trip of the nuclear power plant Oskarshamn 3 at the power of 1400 MW [53]) may then in the worst case cause an instantaneous frequency of 49.0 Hz and a steady state frequency of 49.5 Hz. Based on these criterions and assuming certain kinetic energy and frequency dependency of loads, the FCR-D is dimensioned and the requirement for the regulation response is set. [17]

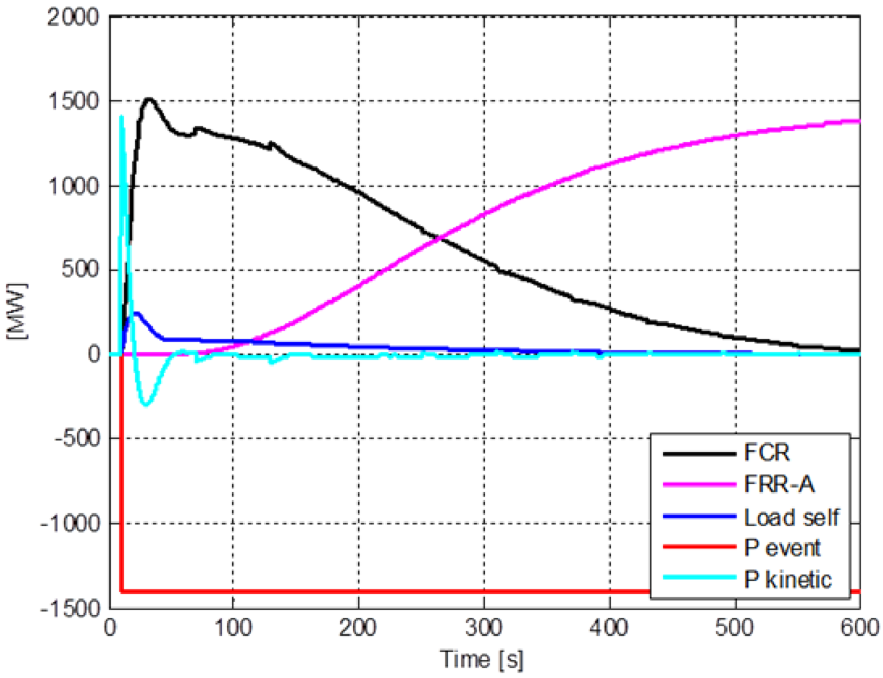

Figure 10 An illustration of calculated power contributions after tripping 1400 MW production. Note: only illustrative figure (not measured response from real disturbance). RAR-model used for simulation [36].

Immediately after the trip of a power plant the power balance is maintained by the transformation of kinetic energy to electrical one as the rotating machines decelerate. This phenomenon gives the FCR-D time to react and to start to increase the mechanical power. The frequency will reach its minimum value when the electrical balance is achieved without support from the kinetic energy. After this, the frequency starts to rise and find its steady state frequency level where lost production due to the disturbance equals the out regulated FCR-D plus change in load due to load frequency dependency.

Figure 10 illustrates the importance of the speed of FCR-D. The amount of FCR-D needed is determined by the Dimensioning Incident and the contribution from the frequency dependent load. [20] [17] [13]

6.9 FRR balancing

The frequency restoration process is handled by manual activation of balancing reserves through the common Nordic balancing market. The responsibility is shared between SN and SvK and the actual balancing is performed via NOIS (Nordic Operational Interface System). Since 2012, this manual activation is supplemented with automatic balancing with a minor available volume. The FRR-A controller is currently located at Statnett.

6.10 Summary and conclusions

Thermal power plants will be tripped by under-frequency relays at around 47.5 Hz for security reasons. This will lead to an even lower frequency and ultimately to a blackout. The FCR and load-shedding schemes have been designed in order to avoid this scenario.

It is the task of FCR-N (and also FRR) to keep the frequency in the normal operating band ± 0.1 Hz. In this way the whole volume of FCR-D is available when a frequency disturbance occurs and the frequency is more likely to be kept above levels where load-shedding starts.

Aspect that affects the need for speed of FCR-D response is the size of the Dimensioning Incident and the amount of stored kinetic energy in the power system. Aspects that affect the amount of FCR-D needed are the Dimensioning Incident and the frequency dependence of load.

Aspects that affect the amount of FCR-N is the load variations and how well production/consumption plans are followed.

If an incident is more severe than the Dimensioning Incident occurs or if part of the FCR-D has been activated before the incident due to an initial frequency below the normal operating band, the frequency drop can be deep enough to initiate load-shedding. This could also be the case if the general system state (inertia, FBF or speed of FCR-D) is other than assumed before the event.

Load-shedding has been designed to avoid a total black-out but involves disconnecting a large number of consumers. Some extra features as the “FANP” with automatic load shedding of electrical steam boilers and electrical heat pumps and emergency support from HVDC exists to avoid automatic load shedding of ordinary consumers. If the incident causing the frequency disturbance is severe enough then not even load-shedding will be sufficient to prevent a black-out.

7. Frequency measurement methods and possible indices

In the following chapter, a discussion is given regarding how frequency physically is being measured and how different frequency indices can be used in the operation of the system.

7.1 Frequency measurement according to standard

IEC 61000-4-30

The frequency reading shall be obtained every 10 s. As power frequency may not be exactly 50 or 60 Hz within the 10-second time clock interval, the number of cycles may not be an integer number. The fundamental frequency output is the ratio of the number of integral cycles counted during the 10-second time clock interval, divided by the cumulative duration of the integer cycles. Before each assessment, harmonics and inter-harmonics shall be attenuated to minimize the effects of multiple zero-crossings.

CENELEC EN 50160

The nominal frequency of the supply voltage shall be 50 Hz. Under normal operating conditions the mean value of the fundamental frequency measured over 10 s shall be within a range of

50 Hz ± 1 % (i.e. 49,5 ... 50,5 Hz) during 99,5 % of a year
50 Hz + 4 %/- 6 % (i.e. 47 ... 52 Hz) during 100 % of the time

for systems with synchronous connection to an interconnected system [4].

7.2 Measurement methods for frequency quality

SvK has measured most of the statistics referred in this report. The frequency is measured with high accuracy (three decimals). It is a redundant measuring system with one measuring unit located in Järva (220kV) and another located in Hamra (400kV). The stored measured frequency of today is integrated over 5 s but the alarm received in the dispatch center use a one second integrated frequency and the frequency registration during disturbances is integrated over 0.1 s.

SvK is calculating the **minutes outside the normal** operating band by using the first 5 s integrated frequency value of every minute. This one sets the value for the whole minute.

Time deviation is continuously calculated with the absolute time and the measured frequency as input. For historical data, hourly values are saved.

The frequency is traditionally defined as the repetition rate of the voltage waveform e.g. the inverse of the time of one cycle. The most commonly used method is based on counting of the zero-crossings of the measured voltage. This is the method as defined in IEC 61000-4-30 for power-quality measurements. The reference [6] describes the pros and cons of this method. It must be immediately noticed that power quality standard requires 10 second average result, but ENTSO-E [8] requires less or equal to one second.

The alternative method for frequency measurement is to measure the rotating frequency of positive sequence of three phase system. This is what the phasor-measurement units do, mostly called PMU units. The advantage is that this method gives an “instantaneous frequency” theoretically with any time resolution, in practise once per cycle. While these units have been used during disturbances it has been demonstrated that instantaneous frequencies are not same in different parts of network, due to machines angle fluctuations. This raises the question of measurement speed needed for frequency quality measurements.

PMU units are recommended for the frequency measurement.

The range in frequency that is allowed according to EN 50160 is far too wide for large synchronous systems and in practice the performance of such systems is much better. The limits according to EN 50160 are thus not of relevance for our study, but the measurement method, using a 10-second interval, could be worth considering. From households point of view 10 second average is certainly fast enough.

[8] Instantaneous Frequency Data means a set of data measurements of the overall System Frequency for the Synchronous Area with a measurement period equal to or shorter than 1 second used for System Frequency quality evaluation purposes.

Instantaneous FRCE Data means a set of data of the Frequency Restoration Control Error (FRCE) for a LFC Block with a measurement period equal to or shorter than 10 s used for System Frequency quality evaluation purposes.

Article 21: The measurement accuracy of the Instantaneous Frequency Data and of the Instantaneous FRCE (if measured in Hz) shall be 1 mHz or better.

The accuracy of most PMU is ±5 mHz for single measurement. The accuracy can be improved by averaging. If there are for example 50 measurements during 1 s averaging period (one measurement each power cycle) the accuracy is improved by the factor of $\sqrt{50}$ to roughly ± 1 mHz.

7.3 Frequency measurement methods and possible indices

ENTSO-E [8] has already determined rather comprehensive list of indices, see Chapter 2. Also in [7], possible frequency indices are being discussed.

From Chapter 5 and [8] it's obvious that four types of indices are commonly used to quantify the frequency quality:

- the standard deviation
- average of the frequency
- the number of threshold crossings
- and the time outside the normal operating band

Maximum synchronous time deviation is also used as target.

Indices related to sudden frequency events are less commonly used. They will require measurements at different locations to obtain accurate estimates. Due to the fact that only a few results per year will be obtained, this is not useful.

Based on Chapter 5 and information given in [8], the commonly used frequency-quality indices are: the total time that the frequency is outside the Standard Frequency Range (SFR) and the number of times that frequency is outside the SFR.

The time interval over which the indices are determined may vary from one week to one year.

The average frequency value and the standard deviation give a good impression of how much the frequency varies around its nominal value.

The maximum synchronous time deviation has been used for a long time. It guides to keep the average frequency close to nominal. It is good indicator how well the reserves has been allocated. It should also be noted that large time deviation means that the average value is shifted and will affect the figure of time outside the SFR. It has been justified earlier also by synchronous clocks, which nowadays have vanishing importance.

In NC LFC&R [8] the standard deviation of frequency is not highlighted as a frequency index. But seen from use in GB, and that in fact give another level of information compared with the "minutes outside normal operating band", it would be seen as a natural factor to follow.

NC LFC&R [11] has stated two averaging times, 1 s for Frequency Quality and 10 s for FRCE Data. The 10 s value is in line with Power Quality standards and sounds more reasonable from end users point of view. The reference [9] shows the differences for results if various averaging times are used. The difference between 1 s or 10 s is rather small, but the 15 min makes substantial difference.

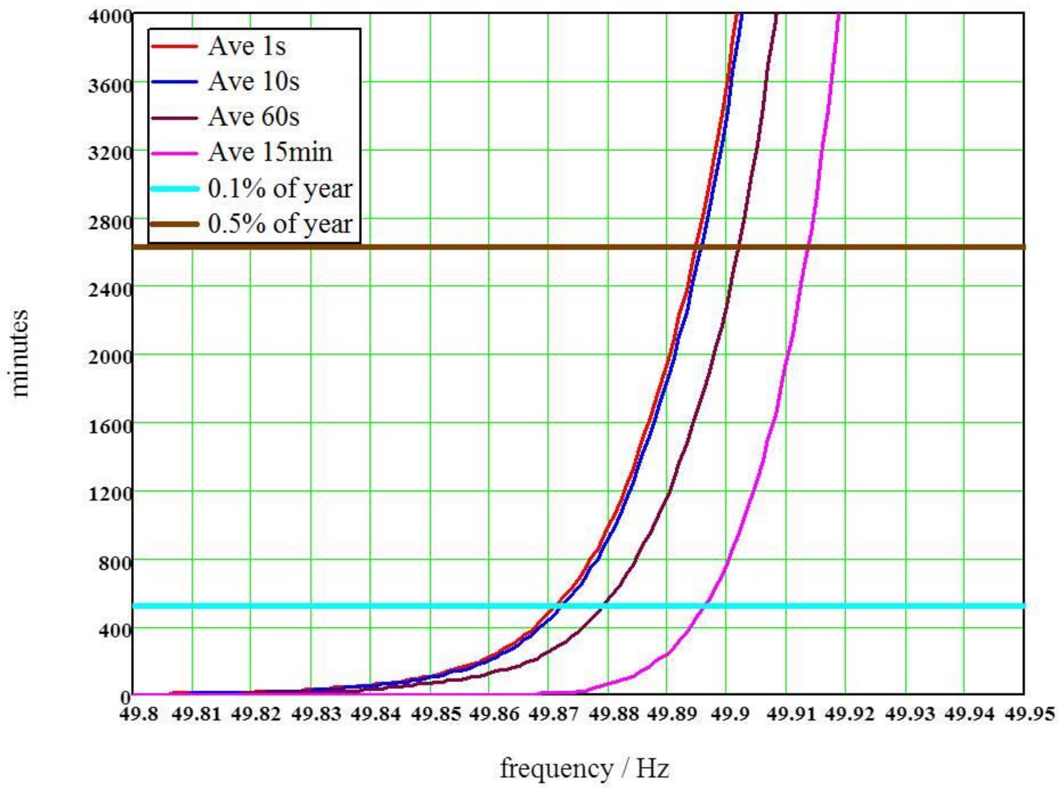

Figure 11 Minutes below the SFR during the year 2008 in Nordic grid measured with different sliding averages.

In Table 1 a comparison between the measurement method of SvK and the use of high resolution (100 ms average) PMU-data has been performed [41]. As can be seen, the difference between the two methods is rather small, an average of the absolute value of 4.3 % for the minutes below 49.9 Hz (2008). From Figure 1, it can be seen that the total minutes outside normal operating band is approximately 6700 minutes. Assuming normal distributed frequency, this means that approximately 3300 minutes below 49.9 Hz. Compared with the value in Figure 11, this corresponds well with the 1 and 10 s average value. I.e. the SvK method gives a value close to a 1 s or 10 s averaging, which in turn is somewhere close to using high resolution PMU data. It is however important to note that a monthly value can differ rather much between using SvK method and high-resolution PMU data.

Table 1 Comparison between SvK method of calculating minutes outside normal operating band with using PMU-data with no averaging method. Percentage value is the difference between minutes outside for a certain month. Negative value equals less minutes outside with SvK method.

	2008		2009		2010	
	>50,1Hz	<49,9Hz	>50,1Hz	<49,9Hz	>50,1Hz	<49,9Hz
January	-0.40%	-1.70%	1.50%	-2.30%	5.60%	-3.50%
February	-2.60%	-1.00%	4.40%	-5.20%		
March	-4.90%	6.30%	4.90%	-2.60%	8.40%	-10.70%
April	13.20%	-5.90%				
May	-4.90%	-6.70%	4.10%	-10.60%	8.20%	-6.80%
June	8.10%	0.70%	3.20%	-11.20%	4.00%	-6.60%
July	8.00%	-15.50%			3.00%	-6.80%
August			-3.60%	-7.30%	3.30%	-8.00%
September	0.70%	-2.20%				
October	1.10%	-8.70%	-0.30%	-4.40%	1.20%	-5.90%
Novermber	0.20%	2.70%	1.60%	0.00%	1.70%	-2.20%
December	2.80%	0.00%	0.40%	-8.90%	4.30%	0.00%
Average	**1.90%**	**-2.90%**	**1.80%**	**-5.80%**	**4.40%**	**-5.60%**
Average of the absolute difference	**4.30%**	**4.70%**	**2.70%**	**5.80%**	**4.40%**	**5.60%**

Indices for Normal operation

NC LFC&R [8] has set the default value for SFR as ±100 mHz.

For all indices, the measurement procedure shall be agreed upon, at least averaging time interval. An averaging time of 10 s is well justified for normal operation and is in line with Power Quality standard [3].

NC LFC&R [8] has defined as default the target for maximum number of minutes outside the SFR per year as 15 000 minutes. TSO:s have a choice to choose different value, but obviously the minutes outside the SFR must be one common index for the synchronous area. Index for shorter time interval is also possible for example one week, which has been used previously as well.

The **standard deviation** together with total average is very descriptive especially for annual statistics, when distribution is very close to normal. Shorter interval distributions may deviate considerably. While distribution can be assumed to be normal then the outside SFR minutes can be easily calculated for any frequency range easily.

The Synchronous Time Deviation (STD) is not literally an index. The agreed maximum STD guides operators to ensure that the average value of the frequency is close to nominal 50.00 Hz. If we assume STD = 30 s during one week period it means that frequency average deviates 2,5 mHz from nominal and will increase number of minutes outside SFR.

Indices for Disturbance

Indices for disturbance is more difficult, because there are rather few incident during one year. The key parameters for each incident are normally analysed:

- Minimum Instantaneous frequency
- Steady state frequency after system has stabilised.

Useful information can be obtained by analysing the rate of change (ROCOF) immediately after the disturbance has occurred. With this and the knowledge of amount of tripped power the total kinetic energy in network can be estimated. While doing these analysis one must remember that after every disturbance there are power fluctuations, which will cause instantaneous frequencies deviates in different parts of grid.

The actual frequency drop during such events is not typically used as a frequency-quality index, although smaller frequency drop indicates better reserve situation. The frequency drop and minimum instantaneous frequency are not recommended for indices, because they depend on many factors out of operators control. Most important ones are the system inertia and FBF.

The instantaneous frequency deviation compared with the steady state frequency deviation can tell something about inertia, frequency depended load and quality of FCR-D, but there is no simple relations between only two elements.

By dividing the tripped power with the steady state frequency deviation (frequency before trip minus steady state frequency), the system FBF can be calculated. This value shall be equal to or above the Dimensioning Incident (trip in MW) divided by the factor 0.4 Hz (49.9-49.5 Hz). It is difficult to set a graded scale for the FBF, and it is probably more suitable to just have a defined acceptable lowest limit.

The measurement time interval has to be sufficiently short to be able to observe the variation of frequency during disturbance. A time interval must be shorter than 1 s, but 100 ms sliding average is seen as relevant.

Using measurements at one location, the accuracy that can be obtained does not seem to be very high. Modern technology, using synchronized measurements at locations spread through the system, are expected to enable a more accurate estimation of these parameters.

In the NC LFC&R [8] the Maximum Instantaneous Frequency Deviation is defined with a default limit of 1000 mHz, and the Maximum Steady State Frequency Deviation with a default limit of 500 mHz.

8. Description of aspects affecting the frequency quality

8.1 Introduction

This section describes more into detail the three different frequency states given in Chapter 4, Normal State, Alert State, and briefly Emergency State. For these the different relevant frequency indices are considered and how different operational aspects and power system parameters affect them.

Several of the aspects/parameters covered in this section are changing over time. This must be kept in mind when a next step is taken and quality indices will be proposed.

Among the aspects that is changing over time and affect the frequency quality the most, are the change of system inertia, the integration of HVDC links, increase of Dimensioning Incident and increase of intermittent production sources (wind power).

- As the NSA has grown larger and more rotating mass has been added, the total kinetic energy in the NSA has become larger overall since the 1980s. Lately, due to the refurbishment of hydropower units where the power output has been maximized and losses reduced, the general belief is that the inertia constant (H) has overall become smaller. However, during the refurbishment of the nuclear power plants in Sweden, the H constant has in several cases actually increased. This implies that the power systems rotating mass might not be declining as much as the general belief is. What is challenging though, is that with the increased number of HVDC interconnectors and the building of new power production with no contribution to the NSA´s kinetic energy, the total rotating mass in the NSA varies more between hours, days and time of the year. [51]
- The number of HVDC interconnectors to the NSA have increased over the last years. It is clear and generally known that the NSA´s installed HVDC capacity affects the numbers of minutes outside the normal operating band, but how much is uncertain.
- When the Dimensioning Incident was introduced in 1975, it was stated that it should be an incident that could occur once every third year. The incident could be an outage or a line trip. The dimensioning was limited to 1200 MW until the power upgrade of Oskarshamn 3 was finished in 2009 and the unit became the world’s largest boiling water reactor. This single change has increased the Dimensioning Incident of NSA with 20 percent. This change shouldn’t affect the minutes outside the normal operating band or the steady state frequency after a

disturbance, but it affects the lowest possible instantaneous frequency as the ROCOF will become greater and in case FCR-D is kept constant.

- The installed wind power capacity in NSA has increased during the last years and is prognosticated to further increase the next couple of years. This intermittent power production does not follow a production plan as accurately as conventional power production due to challenges with accurate wind forecasting, and therefore it affects the minutes outside the normal operating band.

In general, the manual balancing activity is another factor that has a big influence on the frequency quality. However, these manual operational aspects are not further covered in this chapter/report.

8.2 Overall description of the balancing process.

The generation from power units and consumption from loads connected to the ENTSO-E NE network needs to be controlled and monitored for secure a high-quality operation of the synchronous area. The manual balancing, LFC, the technical reserves, load behaviour and the corresponding control performances are essential to keep the grid in operation, which means the frequency deviation have to be within certain limits, Maximum Steady State Frequency Deviation which are 49.5 Hz to 50.5 Hz.

As an example, by increase in the total demand without an increase in the generation the system frequency will decrease, and by decrease in the demand without a decrease in the generation the system frequency will increase.

The Load Frequency Control (manual and or automatic), act as a PI-controller in a closed loop, where frequency containment process, FCP, is the proportional power stabilizing the frequency and the frequency restoration process, FRP, is the integral power controlled by operator or the LFC correcting the frequency towards 50 Hz. Frequency is the controlled quantity and most of the load, some renewable generation and inertia are the not controlled parts of the process in the closed loop.

Within the ENTSO-E CE synchronous area, the individual control actions and the reserves are organised in a hierarchical structure with LFC-areas and LFC blocks, but at present the ENTSO-E NE doesn't have this kind of a LFC-structure. The pilot of FRR-A operating from 2013 have only shown that automatic balancing can reduce minutes outside the standard frequency range. Introduction of an energy activation market (FRR-A market) will probably improve the balancing in the system by more capacity. A more sophisticated system using more LFCs or some other system to control congestions as an enduring solution for automatic balancing are planned to be operational in 2017. Using one or more LFC controllers will give the same result concerning frequency quality.

Load-Frequency Control actions are performed in principle one way, Figure 13, but the **disturbance** has two different origins, Figure 12. Both belong to **Normal State** in the frequency band 49.5 Hz to 50.5 Hz:

- Operation outside normal operating band, outages
- Normal operation, normal load or production imbalances

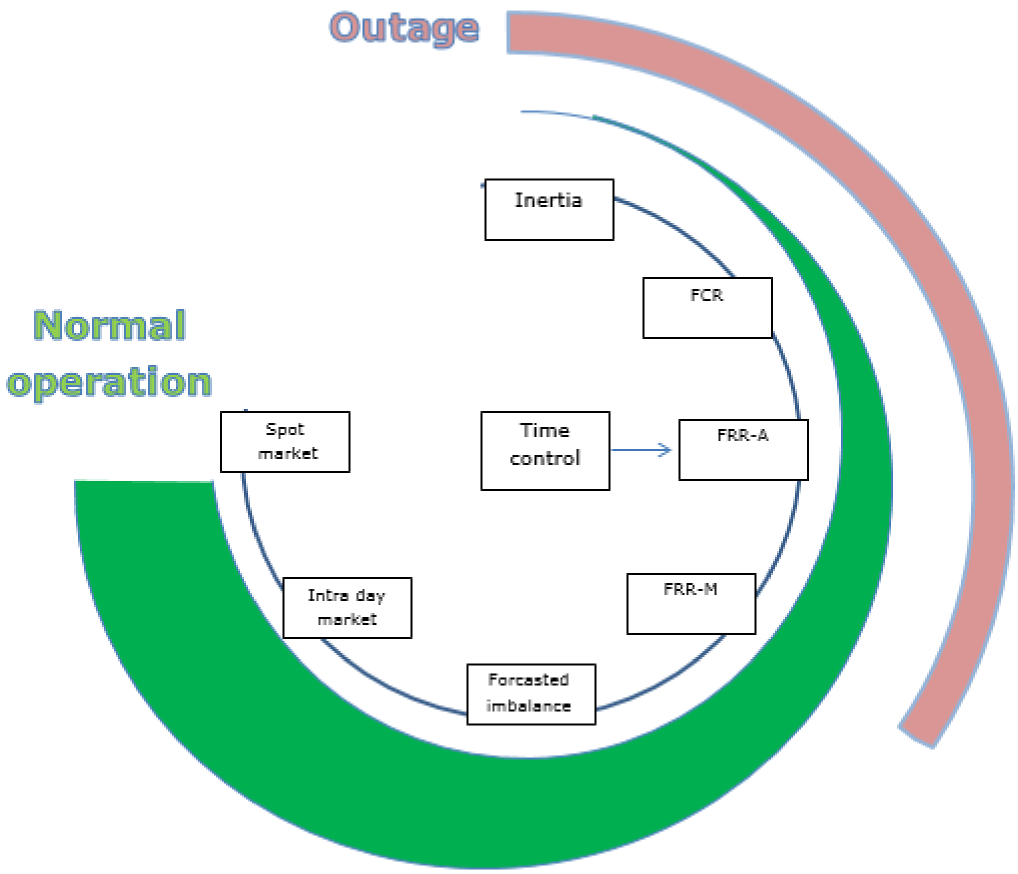

Figure 12 Relations of activated power between Load-Frequency Control elements. The figure indicates, in principle, the relative size of power from spot market to inertia. It should be noted that the activation order for normal operation and operation outside normal operating band is the same, and moves from inertia to FRR-M. I.e. the "time-line" does not continue from FRR-M to spot market, but arrow is continued to show the relative sizes of power.

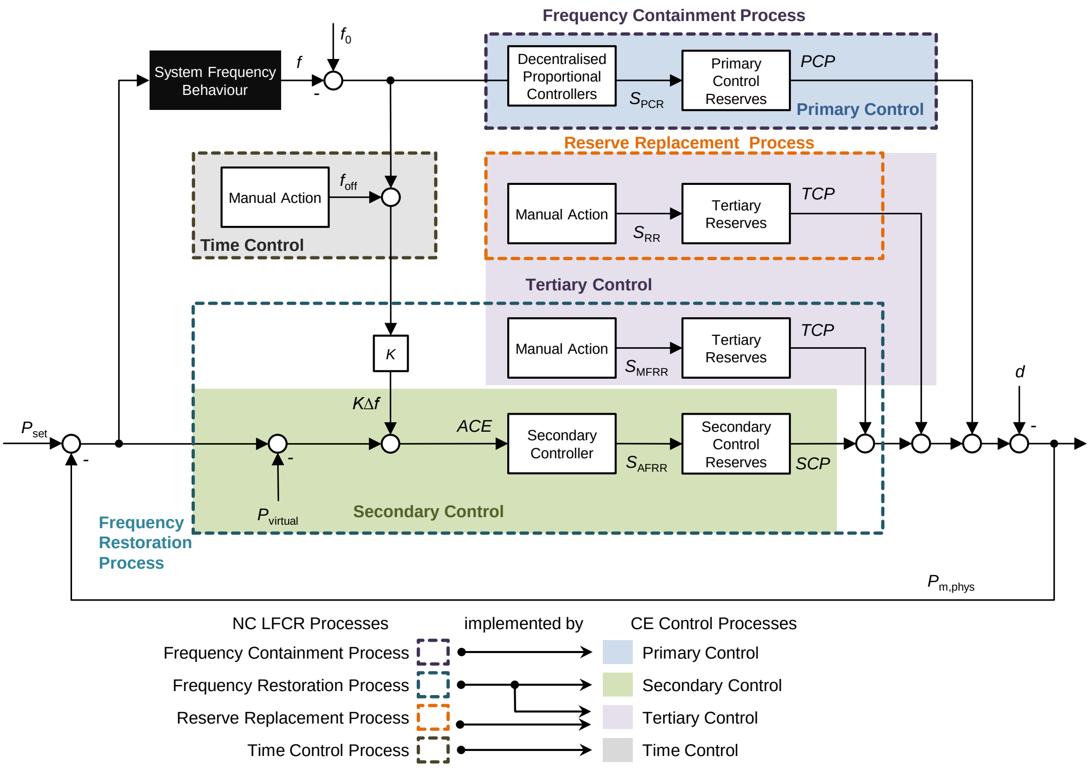

Figure 13 The control loop of the Load-Frequency Control (from Drafting team Policy 1 ENTSO-E CE)

The uncontrolled responses and controlled actions are performed in different successive steps, each with different characteristics and qualities, and all depending on each other, but there is a difference in the activation in the two situations of operation.

The overlapping functions of inertia, FCP and FRP can be seen in Figure 14.

Operation outside normal operating band

In operation outside normal operating band, the balance between power and load are depended on the inherited behaviour of rotating masses and activation of the different control actions in the order:

- Frequency change, damping elements.

  This function will come from the entire synchronous area.

  - Inertia from rotating masses gives immediately after an outage exactly the same power as the outage.
  - Virtual inertia from controllable units as wind turbines and resources with some kind of energy storage.
  - Virtual Inertia from other synchronous areas delivered through HVDC links.

- Frequency containment process, stabilizing elements.

  This process will be active in the entire synchronous area.

  - Elements with a response time much lower than requirement for FCR Full Activation Time.
    - Frequency depended load.
    - Resistant related load as a function of the network voltage.
    - Speed controlled motors.
    - Controllable consumption.
  - Elements with a response time approved to fulfil the requirement for FCR Full Activation Time.
    - FCR from (bigger) loads or generators.
    - Assisting FCR from other synchronous area.
- Frequency Restoration, resets the frequency to frequency set point value.

  This function is controlled by SN and SvK using NOIS regulating power market.

  This function can be done using automatic FRR or manual FRR or a combination of these two principles for activation.

  - FRR-A response starts latest 30 second after LFC signal has been sent from SN. This will solely be activated from the SN FRR-A controller.
  - FRR-M can be activated depending of the situation and the possibilities the affected LFC-area has.

  In this use, after an outage, the sum of the power of the different element will be the same as the outage.

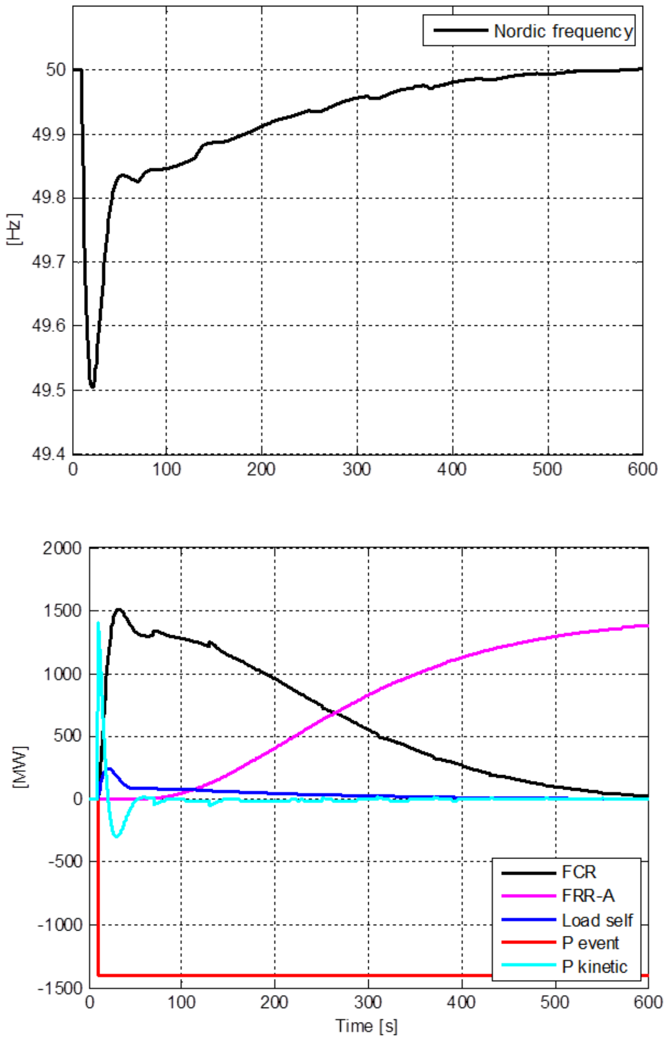

Figure 14 Response of Inertia, FCR and FRR-A after an outage.

Normal operation

In undisturbed operation, the balance between power and load is depended on the activation of the different control actions in the order (only one LFC controller in the synchronous area):

1. Quarterly movements of some of the hourly start/stop of the production will be ordered delayed or moved forward according to prognosis of the imbalances of the synchronous area
2. FRR-M can be activated depending of the situation and the possibilities according to prognosis of the imbalance of area and the actual frequency.

3. Inertia and the other damping elements of all areas reduce the rate of change in frequency and covers for the sum of all imbalances of all areas.
4. FCR in all areas stabilize the frequency and covers a part of the sum of all imbalances.
5. FRR-A will restore the frequency directly in case of only one LFC and indirectly through ACE in each LFC-area. Both solutions will achieve 50 Hz. The activated FRR-A power will cover all imbalances of all areas.

In this use, without an outage, the power of the different element will be much different.

The relations between these elements are different as the dependency of inertia is less than after an outage. Normal operations within the normal operating band consist of many small fluctuations in both load and production, but they are stochastic in size and period length. Figure 15 shows the relations between the elements Inertia, FCR and FRR depending of the period length (imbalance with oscillating characteristic). The response of frequency depended load will act together with the FCR, and can be assumed in this case be included in the FCR-curve.

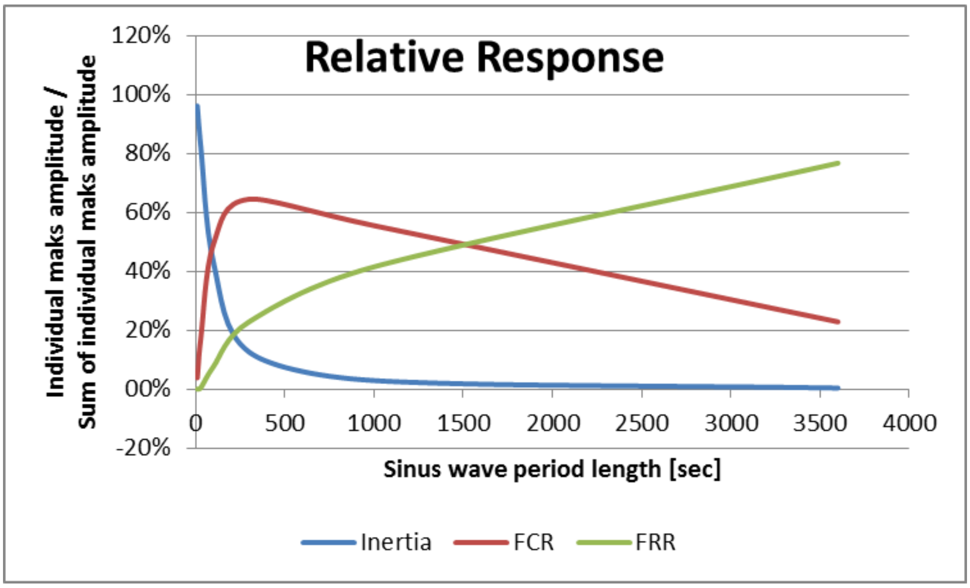

Figure 15 Relative share of response as a function of imbalance oscillations length.

In Figure 15 the relations of the three power suppliers are from simulations with an imbalance power between production and consumption with sinus behaviour that is varied. As the overall power balance is zero the introduced imbalance is covered by the three elements: inertia, FCR and FRR. In the left side – very fast changes of the introduced imbalance – stop/start of production or load - are only covered by inertia. In the right side the ramping of consumption are not using the inertia as the frequency are stable, but offset from target frequency. Sum of individual max amplitude is equal the introduced imbalance.

Figure 16 below illustrate the differences between mechanical and electrical power during a frequency disturbance. Mechanical power is the power delivered from the primary source (steam, hydro), electric power is delivered power from generator to the grid. The difference between these two is the power from inertia.

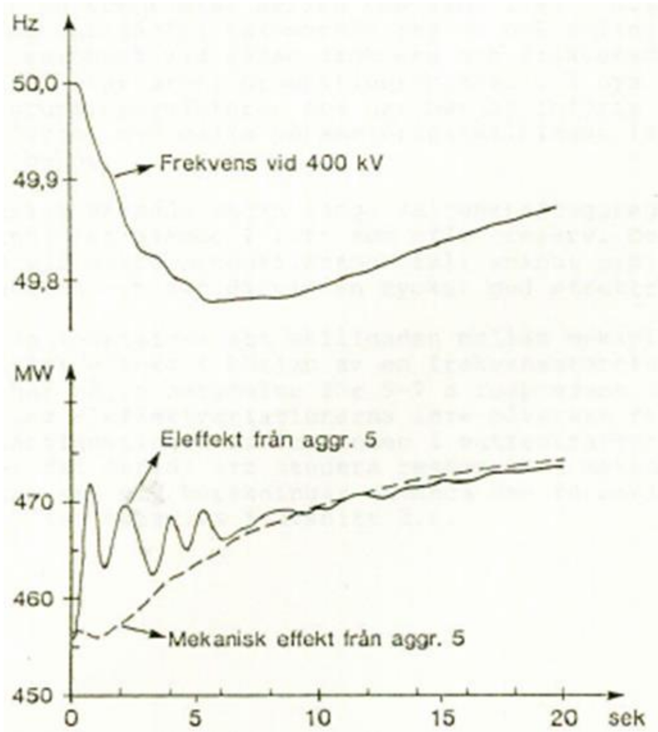

Figure 16 The difference between mechanical and electrical power during a frequency disturbance. [24]

8.3 Relations between Inertia, Rate of Change of Frequency, FBF and speed of FCR

The rate of change of frequency is only depended on inertia and the size of the disturbance.

In case of little inertia the requirement to the response time of FCR increase and in case of requirements to steady state frequency is 49.5 Hz this also increase requirement to speed of FCR. These relationships were investigated in RAR [36] as well as in Fingrid study [37].

In the RAR report [36] the relation between required speed of FCR and frequency bias factor was also compared to the systems inertia. Figure 17 gives an illustration of this comparison.

For a low value of inertia (50 GWs)[17] and a low value of FBF (3250 MW/Hz), the FCR response needs to be 10 sec or faster to prevent the frequency from going below 49.2 Hz.

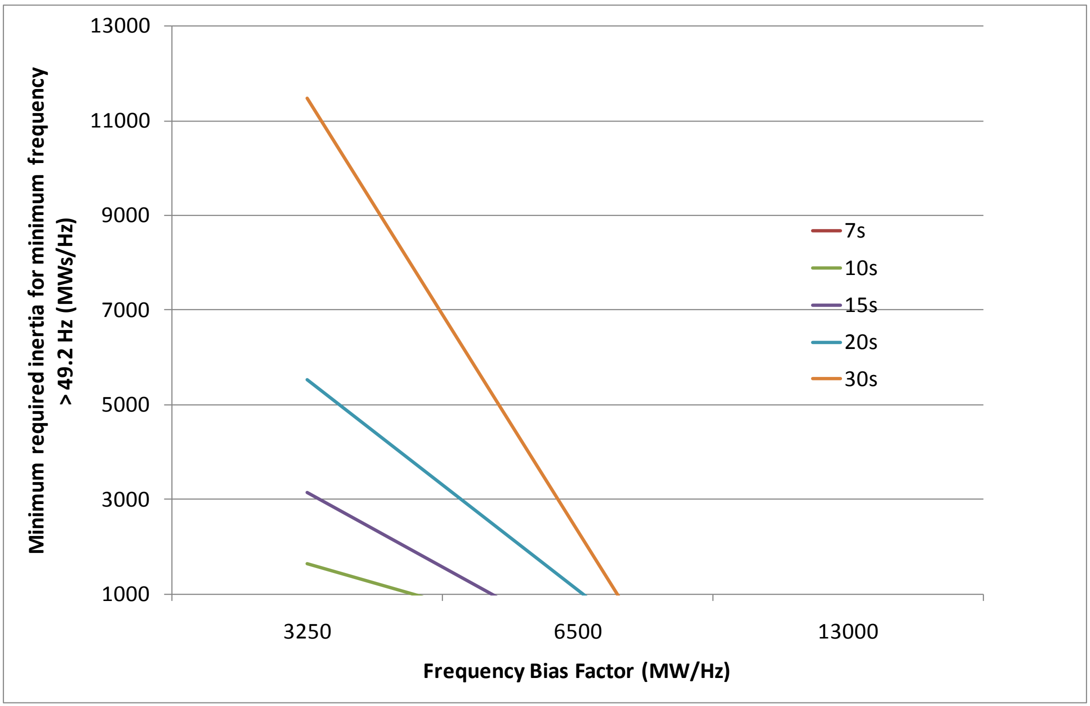

Figure 17 Minimum inertia in the system that is required for keeping the minimum frequency above 49.2 Hz for several values of the Frequency Bias Factor for different system time constants of the FCR-D [36]. See also footnote 17.

8.4 60 sec oscillations

As described in Chapter 2 (Introduction), there is an ongoing project called "60s project" studying the oscillation of the frequency in the NSA[18].

The reason for the oscillations is a result of

- Load variations with a wide frequency range (i.e. approximated to white noise)
- A resonance peak within the FCR contributing units close to a period time of 60s.
- For some FCR contributing units a phase shift (frequency to active power) that excites the oscillations within the studied period time.

Analyses within the project show that increased inertia and frequency dependency for loads are system parameters that positively contributing to reducing oscillations. The analyses also

[17] In [38] the unit MWs/Hz is used. H [MWs] = H [MWs/Hz] x 25.

[18] At the moment of writing, the reports from phase 1 and 2 has still not been published.

show that amount of FCR per unit (distribution), total system FCR volume, proportional constant within governors and back lash (see 8.5) are examples are factors that affect the amount of oscillations.

If the average value over several minutes is somewhere close to the thresholds for normal operation, it is obvious that an overlaying oscillation will make the momentarily frequency move outside the normal operating band. Investigation made by Fingrid [41] show that half of the minutes outside the normal operating band are being caused by oscillations. The amount of oscillations are varying over year (and within hour and minute) as seen in Figure 19.[19]

Seen in the light of the "60s project", it would be natural to create a frequency quality index that captures the amount of oscillations. As given in chapter 3, this is however not a part of this work.

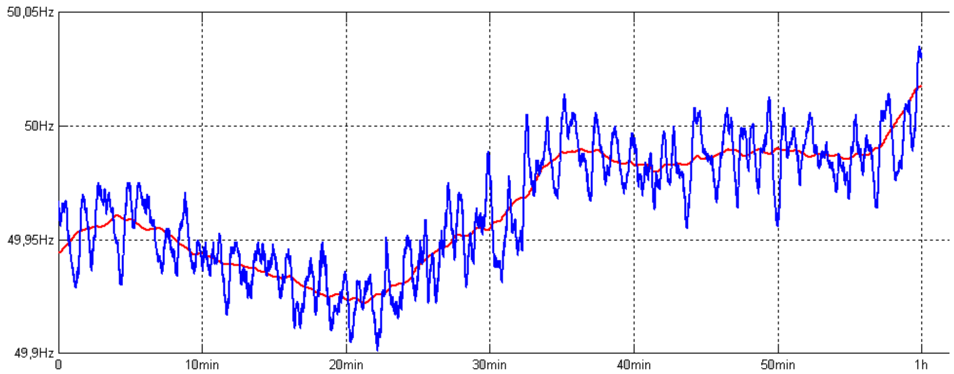

Figure 18 Original frequency measurement (blue) and a filtered frequency (eliminating the 60 s oscillation) (red) [41]

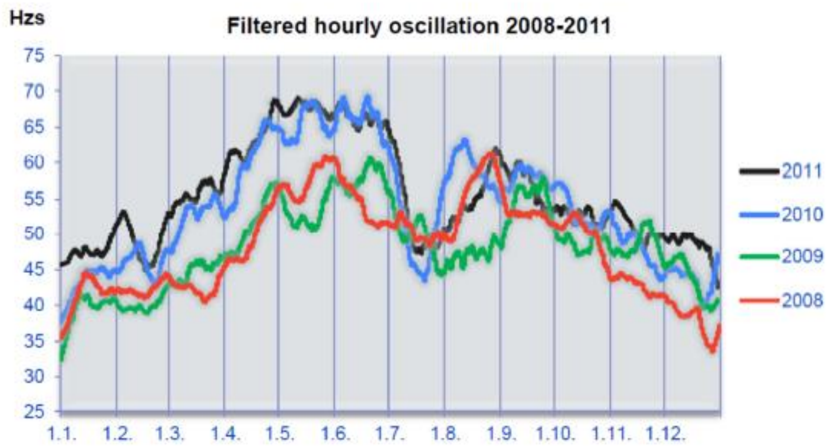

Figure 19 Amount of oscillations during year 2008-2011 [see footnote 4]

[19] The next phase of the 60s project will aim at creating a harmonized technical specification for turbine governors providing FCR-N/D to the Nordic synchronous system.

8.5 Dead band

In control theory there are more elements where the word dead band is used, but the physical difference are not the same. The three different meanings are:

- Insensibility
  This is the insensibility of measurement, i.e. resolutions of measurements from frequency to position and power measurements.
- Intended dead band
  This is the band where it is expected no response will take place. E.g. dead band of +/- 100 mHz from 50 Hz for FCR-D.
- Backlash
  This is hysteresis coming from mechanical dead band, a set point change don't give change in output.

The NC LFC&R [8] distinguishes between inherent Frequency Response Insensitivity and possible intentional Frequency Response Dead band. The article 44 of NC LFC&R [8] states the maximum combined effect of inherent Frequency Response Insensitivity and possible intentional Frequency Response Dead band of the governor of the FCR Providing Units or FCR Providing Groups is 10 mHz in the Nordic area.

8.6 Normal operation

This chapter will describe factors that mostly has an impact on the frequency quality in normal operation. These ones comes in addition to the aspects in previous chapters.

In general, and as stated earlier in the report, frequency deviating from the nominal comes from imbalances between production and loads.

Power produced by power plants and the transmissions of HVDC-links change from hour to hour according to their schedules. This creates momentary imbalances at top of the hour. These imbalances can be predicted to some extent, but not completely, as power plants do not follow their schedules exactly.

Loads do not normally follow hourly schedules but are instead varying continuously during each hour. This creates random imbalances that cannot be predicted even though hourly load variation pattern can be roughly forecasted and taken into account by purchasing balancing power proactively. Forecasts always have some error, which results in imbalances as the generation schedules fail to match the forecasted loads.

Wind power adds still another component to the random imbalance. The reference [1] gives some indications. The report considers hourly statistics and has simulated different levels of wind power penetrations. One observation has given: "The 2000 MW in Denmark increases the variations by 1% (20 MW), and the same penetration level for Finland, 4000 MW, increases the variations by 2% (80 MW)". On Nordic level the report estimates that 20% energy penetration will increase hourly variation of 2% of installed wind capacity.

HVDC-links are able to change their power fast and their number in the Nordic power system has increased. The electricity market also uses their capacity extensively, which leads to high changes of power transmitted through them. It has therefore been necessary to limit the magnitude and speed of those changes. The limits are set to 600 MWh/h and 30 MW/min per HVDC-link. [2]

Time deviation

Modern clocks do not depend on power system frequency for keeping their time. There is however still a requirement in NC LFC&R [8] for time deviation, but is not mandatory for the NSA[20].

The supporting document of NC LFC&R [28] specifies: "The mean value (of frequency) is widely used indicator of control performance and should be almost exactly 50 Hz if combined over three month and proportional to electrical time deviation. The mean value of Instantaneous Frequency Data can be used to detect deterministic tendencies of imbalances (short or long) but also different control qualities into upward and downward direction."

The reference [8] says also that there can be unforeseeable consequences of omitting a requirement for Time deviation. There can for instance still be old electrical meters calculating different tariff periods and old industry processes dependent on time derived from network frequency.

The document [28] also points out that "significant electrical time deviations are proportional to the energy amount delivered due to FCR activation", which in turn is linked with pricing of reserve power and is consequently an economic issue.

Correcting the target frequency to correct the time error will affect the minutes outside the standard frequency range to some extent. If the frequency is higher than 50 Hz for some hours, this is can result in more minutes above 50.1 Hz. The time error caused by this over-frequency

[20] Time Control Process *may* be included for the NSA according to Article 31 NC LFC&R [8].

will need to be corrected by a slight under-frequency for some time, which can result in some more minutes below 49.9 Hz.

Dimensioning of FCR-N and FRR

Aspects that affect the amount of FCR-N is the load variation, the amplitude of frequency oscillations, how well organized the operational monitoring and control are and how fast the secondary regulation can be. The needed amount of FCR-N is closely linked to the imbalances in normal operation.

As explained in Chapter 6.8, the basis for the present practise [2] for dimensioning of FCR-N is based on an historic assumption of maximum load of 60 GW and load random variation of 1%. To compensate the load variation there is a need for 600 MW of FCR-N. The load variation is most of the time normally distributed (Gaussian) and therefore it can be expected that for a fraction of the time, the load variation is larger than the available resources.

The Manual Frequency Restoration Reserves (FRR-M) is currently dimensioned based on the amount of power production that can be lost in a single fault. Each country shall be able to balance its power by having an amount of FRR-M that equals the power lost in the Dimensioning Incident of the country.

There is currently, on a Nordic level, no agreed method for dimensioning Automatic Frequency Restoration Reserves (FRR-A). A method is described NC LFC&R [8]. In the RAR report [36] there were made simulations to study the influence of minimum FRR-A volume and the requirements for the speed of the LFC-control loop. Figure 20 summarize this relationship. Further on, Table 2 gives a result for the corresponding study between different volumes of FCR and FRR, and the resulting frequency quality.

Table 2 The impact to minutes outside the standard frequency range can reduce from 23.3 to 0 minutes/day by introducing 600 MW FRR-A [42]

	Volume FRR			
Volume FCR	**0**	**200**	**400**	**600**
400	559.0	158.7	31.3	18.3
600	216.7	35.3	5.0	0.7
800	75.0	10.3	1.3	0.0
1000	25.7	4.3	0.7	0.0
existing	23.3			

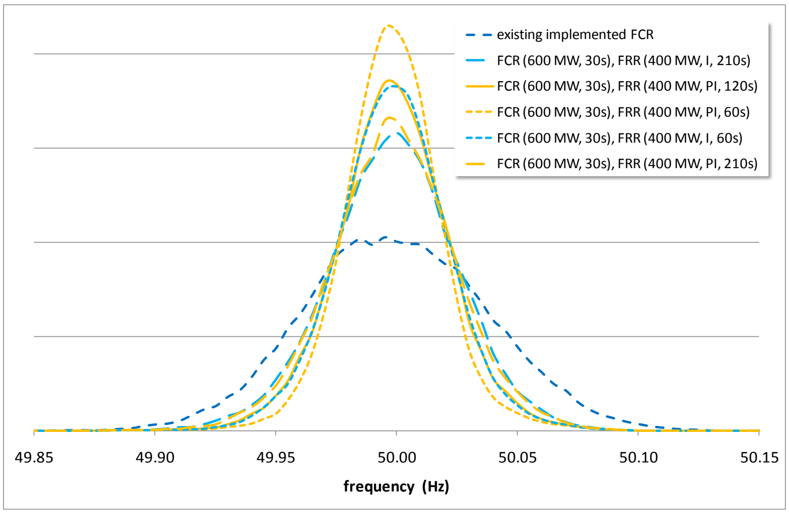

Figure 20 Different setting and requirement for the response of FRR-A will all fulfil the need - keep the frequency within the Standard Frequency Range [36].

In 2013 the LFC Implementation Group evaluated different settings in the LFC controller by actual testing, and found that two different speed of LFC-controller gave nearly the same improvement of frequency quality (footnote 29 [42]). The difference was found to be 0.3 % versus 0.4% of time outside the normal operating band using integration time of 200 s versus 400 s. Due to the relative small volume of FRR-A in this implementation study, this must be seen as only indicative figures.

8.7 Operation outside normal operating band

Frequency level prior to disturbance

Currently it is assumed that the system is at 50 Hz when the disturbance occurs. However, from the frequency statistics it is clear that normal operation is often significantly below 50 Hz. Figure 21 below shows the frequency distribution for "as is" and with a modified set up in the existing governors in the Nordic synchronous system [36].

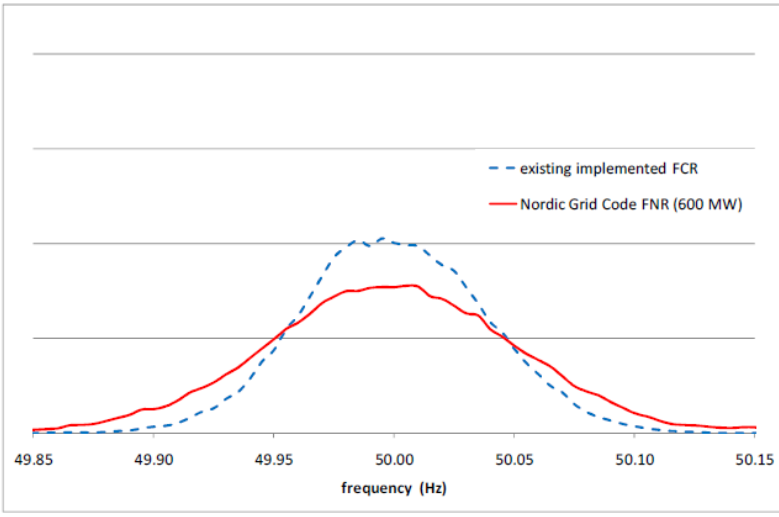

Figure 21 Normal frequency distribution – example only replace with Fingrid PMU data 1 min resolution.

An initial frequency below 50 Hz before a disturbance will result in frequency response that differ from a case where the initial frequency is at 50 Hz. A part of FCR (-N and possible –D) will be activated and not available for the recovery phase.

Impact of frequency bias factor and inertia to frequency drop

When an disturbance occurs, for instance tripping of a large production unit, there will be a frequency drop with a magnitude highly dependent on the system inertia and frequency bias factor, together with other factors as frequency dependency of loads and speed of control of reserve power.

As described in section 6.8, the inertia/kinetic energy that is stored in rotating units (producers as well as consumers) synchronous connected to the synchronous system will result in an active power injection at the moment of disturbance when kinetic energy is converted to electrical energy. During a frequency drop, this "inertial response" is added to the system when there is a frequency derivative as indicated in the shaded area in Figure 22 below.

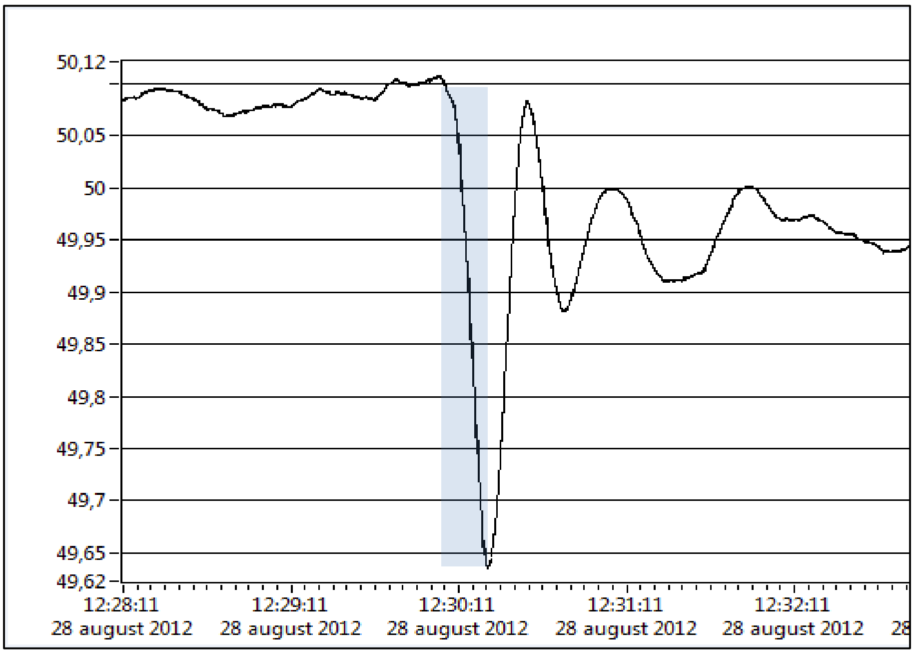

Figure 22 Frequency during a loss of larger production unit in the Nordic synchronous system. Area of inertial response highlighted.

The inertial response (time from disturbance to activation of FCR and frequency nadir) has a duration of roughly 5-10 s. When the frequency derivative is zero (minimum frequency), there is an equilibrium state where the produced mechanical power together with the additional power coming from transformation of kinetic energy is equal to the electrical power in the system. At this state, there has been an injection of kinetic energy together with the first part of the response of the system FCR. Continued FCR-contribution will result in a positive frequency derivative taking the frequency back to a steady state somewhere between the minimum frequency and nominal frequency.

The “frequency controlled disturbance reserve” (FCR-D) is available for the frequency range from 49.5[21] to 49.9 Hz. For a Dimensioning Incident (defines as a loss of 1400 MW of production, see section 6.8) this reserve should be sufficient to maintain the steady state frequency above 49.5 Hz (see section 4). Half of this reserve should be available within 5 s, the remainder within 30 s. The total amount of FCR-D in the NSA is 200 MW less than the Dimensioning Incident.

The following is the relation between inertia, system base power, frequency, frequency derivative and power imbalance.

[21] I.e. **f**ully activated at 49.5 Hz [2]

$$H_{\mathrm{tot}} S_{\mathrm{n}} = \frac{1}{2} f_{\mathrm{n}} \frac{dt}{df} \Delta P$$

where

H_{tot} is the system inertia,
S_{n} is the total rated apparent power,
f_{n} is the rated frequency,
df/dt is the frequency derivative
ΔP is the power imbalance.

It is obvious that an increased system inertia will result in a lower df/dt (for all other parameters fixed). A lower value of df/dt means that it would take longer time to reach the same frequency minimum point compared with a situation with *lower* inertia.

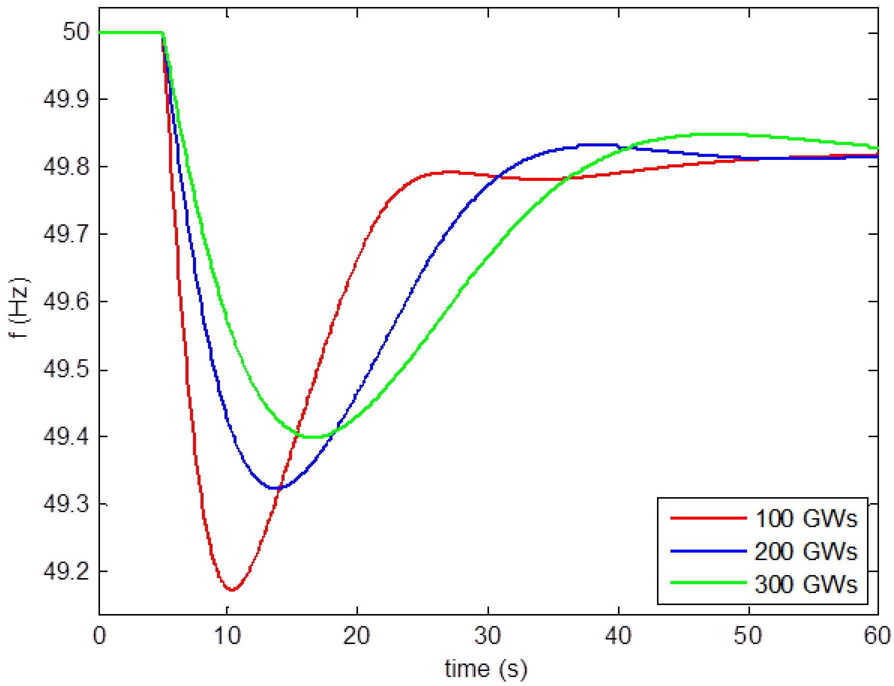

Figure 23 Simulated response for frequency response when losing a large generating unit, as a function of different system inertia levels.

The total frequency bias factor (FBF[22]) [MW/Hz] in the system has an impact on the frequency drop. As explained above, at the equilibrium state when frequency derivative is equal to zero, there is the first initial part of the FCR being added to the system balance.

$$FBF = \frac{\Delta P}{f_0 - f_{steady\ state}}$$

However, speed of response of the FCR will have a big impact on the contribution to limit the frequency dip as can be seen in Figure 24 and Figure 25.

An increased FBF decrease time to minimum frequency level and also the actual value of minimum frequency level.

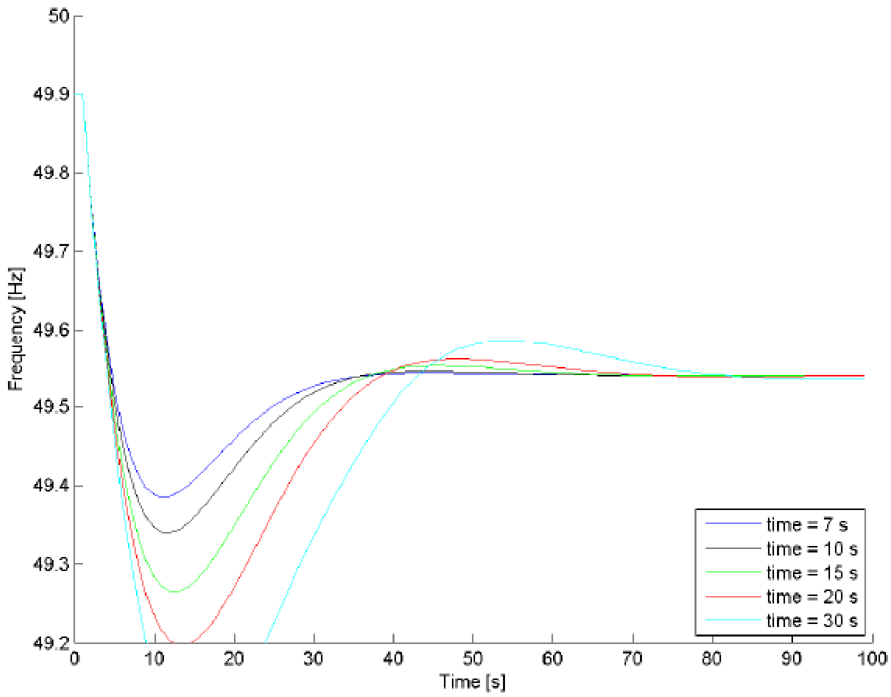

Figure 24 Relations between speed of FCR and frequency network characteristic for steady state frequency of 49.5 Hz (frequency deviation after outage is 400 mHz). Loss of production is 1300 MW, FBF 3250 MW/Hz, Inertia 250 GWs [36].

[22] The frequency bias factor is the derivative of the FCR-N + FCR-D response (inclusive load frequency dependent load, HVDC contribution etc.).

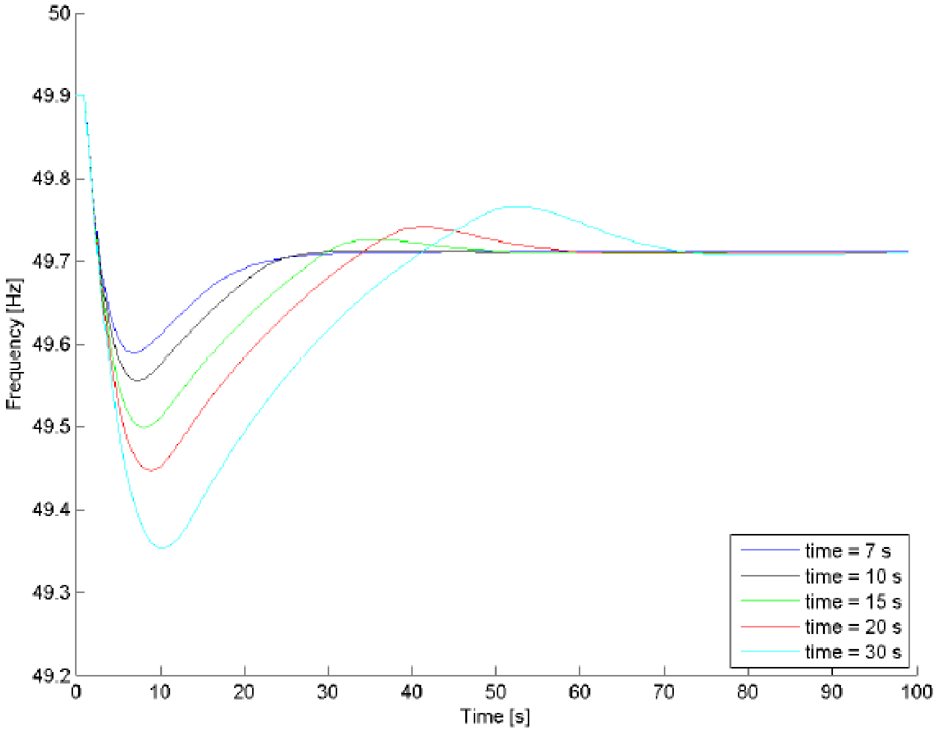

Figure 25 Relations between speed of FCR and frequency network characteristic for steady state frequency deviation of 49.7 Hz (frequency deviation after outage is 200 mHz). Loss of production is 1300 MW, FBF 6500 MW/Hz, Inertia 250 GWs [38].

In RAR-report [47] it is specified that the actual FBF is higher than the required amount in specified in the grid code. The current Nordic grid code requires that 600 MW of FCR-N is activated at a frequency deviation of 0.1 Hz, equal to 6000 MW/Hz in the band 49.9 to 50.1 Hz, and 1200 MW/(49.9-49.5 Hz) equal to 3000 MW/Hz for frequency between 49.5 - 49.9 Hz.

If reducing the volume of FCR-D to the level required in the grid code (1200 MW), a steady state frequency will be kept above 49.5 Hz for the Dimensioning Incident. It does however not guarantee that the instantaneous minimum frequency exceeds a certain value. The minimum instantaneous frequency depends also on the speed at which FCR is activated, as illustrated in Figure 24 and Figure 25. As seen, if reducing the amount of FBF from the present "normal value", to the level given by the requirement in the grid code, the speed of response needs to be improved if the minimum instantaneous frequency shall be kept at the same level.

From equation for FBF above, it is obvious that there are parameters vitiated with uncertainties. These are:

- ΔP
  The actual imbalance depends on the total load reduction during the frequency disturbance. Frequency dependency for loads are further described in section 0.
- H
  This factor can be estimated in real time. However, this is a best guess and not a measured and validated number. System inertia constant can be measured (or calculated from measured frequency response) *after* a disturbance. Also the FBF is vitiated with uncertainties.
- The speed of response for FCR-N/D is somewhat spread [54] and in certain cases there are indications that units are slower compared with present grid codes.
- On the other hand is volumes of FCR-N/D often larger [36] then stipulated, which to some extent mitigate the weaker speed of response (as can be seen in Figure 24 and Figure 25).

Impact of self regulation of load

Different load types in the system behaves differently regarding power consumption during a situation where voltage and/or frequency deviates from their nominal values. This is called "self regulating" of load.

It is foremost direct driven asynchronous motors that have a large frequency dependency. Dependent on the primary load, the dependency is different (constant, linearly, quadratic, cubic etc.). See [31] for further details regarding loads and their behaviour.

It has been estimated that the frequency dependence of loads is 1 % for a frequency variation of 1 Hz in the NSA. The last study from 1995 [5] gives a figure 0.7 % / Hz for a low load situation.

Based on the ratio factor given above, currently 200 MW of load in the Nordic synchronous system is assumed to be self – regulating regarding frequency for the Dimensioning Incident [2] and thereby for the dimensioning of FCR-D. Per today, this means that the Dimensioning Incident is defined as the loss of largest single unit reduced with a power amount equal to 200 MW.

In NC LFC&R the following is specified:

2. The TSOs of a Synchronous Area shall determine at least on an annual basis the size of the K-Factor of the Synchronous Area taking into account factors including, but not limited to:

   a) The FCR Capacity divided by the Maximum Steady-State Frequency Deviation;

   b) the auto-control of generation; and

   c) the self-regulation of load taking into account the contribution according to the [NC DCC Article 21 and 22].

How the self regulation shall be considered is to be defined in a Nordic agreement process when setting requirements for FCR-D.

Impact of fault location on minimum frequency level

Due to voltage dependency for loads (see section 0), there system frequency response during a disturbance can differ for the same amount disconnected production (or consumption). As an example, a loss of production of 1000 MW in south of Sweden will give another system frequency response compared with a trip of a 1000 MW production in south of Finland.

The reason for this is the different power flow and resulting voltage dip. "Moving power" to the south of Sweden over the cross section will result in a voltage reduction, and thus reduction in load (due to voltage dependent loads). This voltage reduction and reduction in load will be larger compared to if the same production would be lost in south of Finland.

I.e. the power imbalance for the same production loss will differ, and thus creating different frequency response in the system. It affect both min frequency and steady state frequency.

Steady state frequency level, time to restore frequency

After a disturbance, the frequency will recover to a steady state level. This level is dependent on the amount of FCR available together with initial frequency level before incident as well as amount of self regulating load in the system. The frequency level can be calculated as:

$$f = f_{nom} - \frac{P_{loss}}{R}$$

Where

R is the Frequency Bias Factor [MW/Hz]
f_{nom} is the nominal frequency
P_{loss} is the loss of active power [MW]

As stated in Article 19, NC LFC&R [8] specifies the Maximum Steady State Frequency Deviation to 500 mHz. This is in line with the present limits and requirements for FCR-D, which shall be fully activated at 49.5 Hz.

The current SOA states that after an N-1-fault the system shall be brought to a state where it can withstand any N-1-fault within 15 minutes. Based on this the time to restore the frequency to normal operating band after any Dimensioning Incident is currently 15 minutes.

9. Analysis results- frequency quality levels

In the following chapter the two different aspects are being analysed:

- The impact on probability to fall below a frequency level of 49.0 Hz as a result of different number of minutes outside normal operating band.
- The impact on minimum frequency level as a result of different FBF and inertia in the system.

These analyses will reveal the impact of different quality levels when it comes to minutes outside normal operating band as well as the impact of different system parameter on the minimum instantaneous frequency level during a Dimensioning Incident.

9.1 Analysis of different levels of minutes outside normal operating band

RGN has 19.11.2013 agreed on target (maximum) number of 10 000 minutes outside the normal operating band for year 2014. This target is not a fixed one but will be reviewed yearly.

If frequency is outside the boundaries 50 ± 0.1 Hz in normal operation for some percent of time does not significantly increase the risk of frequency going under 49 Hz as the following analysis shows.

According to the current Nordic System Operation Agreement there shall be in total 1200 MW frequency controlled disturbance reserves (FCR-D). The frequency controlled disturbance reserve shall be activated at 49.9 Hz and shall be fully activated at 49.5 Hz. It shall increase virtually linearly within a frequency range of 49.9-49.5 Hz.

The activated amount P of FCR-D can be calculated based on the equation (1), when the initial frequency finit is in the range 49.5...49.9 Hz:

$$P = (49.9 \text{ Hz} - f_{init}) * 1200 \text{ MW} / 0.4 \text{ Hz} \qquad (1)$$

Table 3 Activated FCR-D when the initial frequency is below 49.9 Hz.

		Number of minutes per year outside the range 49.9...50.1 Hz		
		10000	15000	20000
Frequency limit (Hz)	Acivated FCR-D (minimum)	Minutes when activated		
49.88	50	1635	2792	4078
49.87	100	465	921	1493
49.85	150	114	268	489
49.83	200	24	69	143
49.82	250	5	15	38
49.80	300	1	3	9
49.78	350	0.1	0.5	2
49.77	400	0.01	0.1	0.3

As stated in Chapter 6.8, the Dimensioning Incident in the Nordic power system is the trip of the nuclear power plant Oskarshamn 3 at the power of 1400 MW. The next most critical incident can lead to the loss of 1200 MW of production in Norway. There are thus two possible incidents that can cause power deficits higher than 1200 MW. The rest of the individual n-1 -incidents are considerably less severe. They include trips of other large nuclear units. There are in total five possible incidents that can cause power deficits higher than 1000 MW.

Severe frequency disturbances have in practice occurred seldom as the Table 4 shows. The Dimensioning Incident obviously occurs more rarely but the same figures can be conservatively used to estimate the occurrence of disturbances severe enough to be able to cause frequency dips lower than 49 Hz.

Table 4 Frequency disturbance statistics of the time period 30.10.2003 - 10.3.2014

f <	Incidents /year
49.5 Hz	0.8
49.4 Hz	0.2
49.3 Hz	0.1

Let us assume that the frequency controlled disturbance reserves would be dimensioned to ensure that the minimum instantaneous frequency always stays above 49 Hz after the Dimensioning Incident, occurring when the frequency is 49.9 Hz. It would follow that an initial frequency lower than 49.9 Hz could lead to a minimum instantaneous frequency below 49 Hz because not all FCR-D would be available when the Dimensioning Incident occurs. Based on this reasoning, the Table 5 presents estimated mean times between incidents with frequencies under 49 Hz with different numbers of minutes outside the normal frequency range.

Table 5 Estimated mean time between incidents involving frequencies below 49 Hz assuming that each of the critical incidents leads to a frequency drop of 0.9 Hz when the initial frequency is > 49.9 Hz and all FCR-D is thus available

	Number of minutes outside the range 49.9...50.1 Hz		
	10000	15000	20000
Number of critical incidents / year	Mean time between incidents (years)		
1	105	70	53
0.5	210	140	105
0.1	1051	701	526

Table 5 shows the occurrence of incidents with different levels of severity. The following figures give more detailed information on the same statistics.

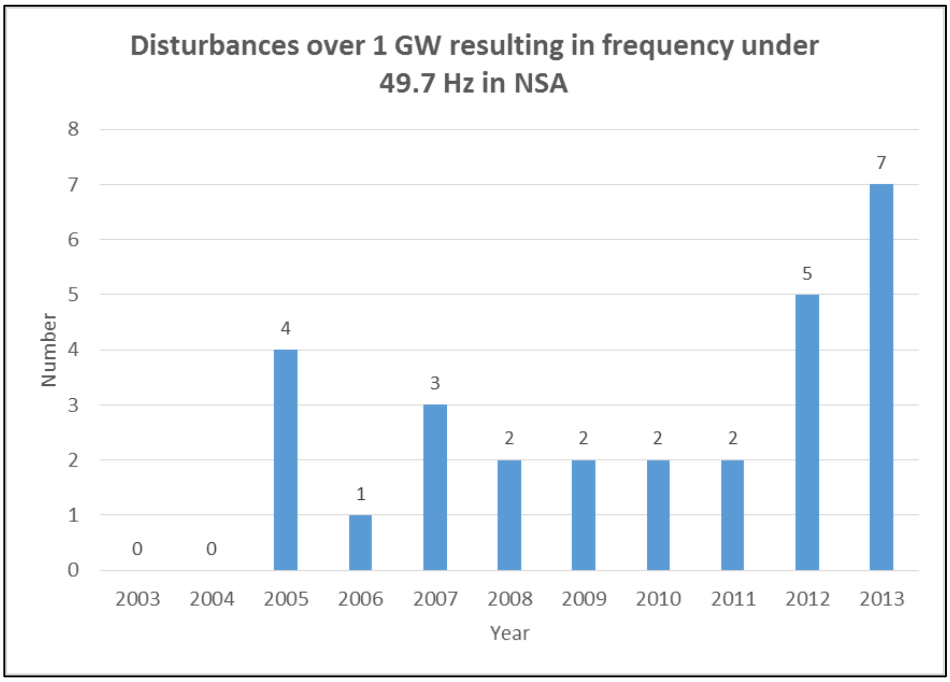

Figure 26 Statistics on annual numbers of frequency drops below 49.7 Hz in the NSA.

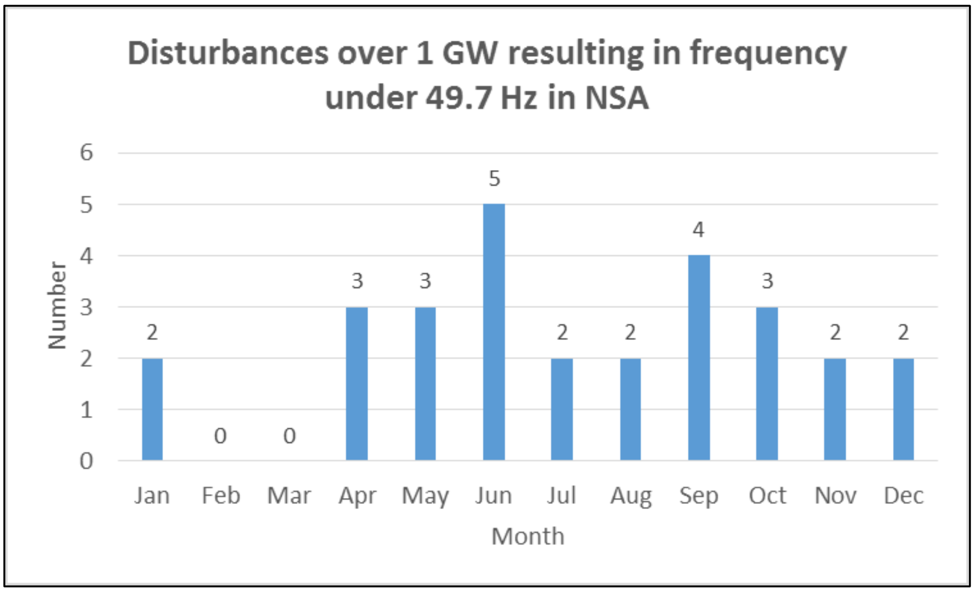

Figure 27 Monthly distribution of frequency drops deeper than 49.7 Hz in years 2003-2013.

9.2 Analysis of minimum frequency level for different FBF and inertia

The maximum frequency drop depends on many factors: tripping production, inertia, frequency dependency of loads and speed of control of reserve power. Some aspects have has been emphasized in reference [10]. It gives brief statistics about large frequency drops during the years 1999 -2013. There are 12 incidents when frequency has dropped below 49.5 Hz and three incidents when frequency has been under 49.3 Hz.

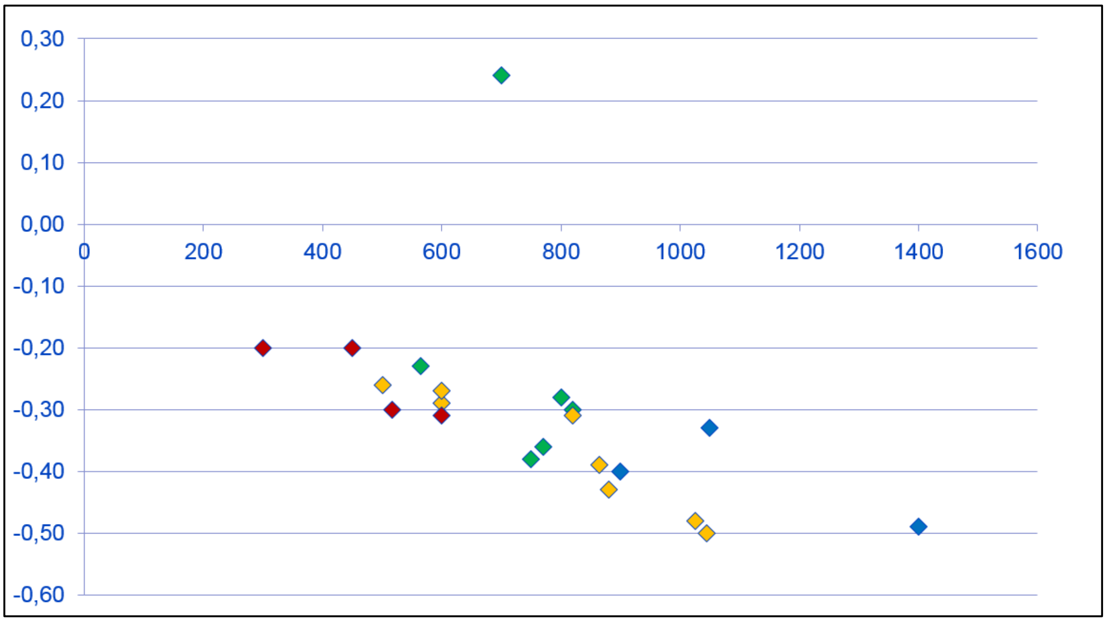

Figure 28 Frequency drop (Y-axis) vs tripped power (X-axis) in disturbances 2009-2012. Inertia: ***< 150 GWs*****,** ***150-200 GWs*****,** ***200-250 GWs*****,** ***250 -300 GWs***

9.3 FCR-D Obligations in Nordic Synchronous System

In the present SOA [2] the following is stated:

"There shall be a frequency controlled disturbance reserve of such magnitude and composition that dimensioning faults will not entail a frequency of less than 49.5 Hz in the synchronous system."

…

Taking into account the frequency-dependence of consumption, the above requirements entail that the combined frequency controlled disturbance reserve shall amount to an output power equal to the dimensioning faults less 200 MW.

In the simulations below, an instantaneous net imbalance of 1200 MW has been assumed, which comes from a Dimensioning Incident of 1400 MW and a reduction of load of 200 MW due to the frequency dependency.

The reserves has been agreed between TSOs, and is according to figures in Table 6 and Table 7. [2]

Table 6 Present FCR-D obligations approximately

Norway	Sweden	Finland	Denmark	Total
353 MW	412 MW	259 MW	177 MW	1201 MW

Table 7 Typical time constants for step response

Norway	Sweden[23]	Finland	Denmark
25 s	60 s	7 s	60 s

Illustrative simulations, obligatory reserves

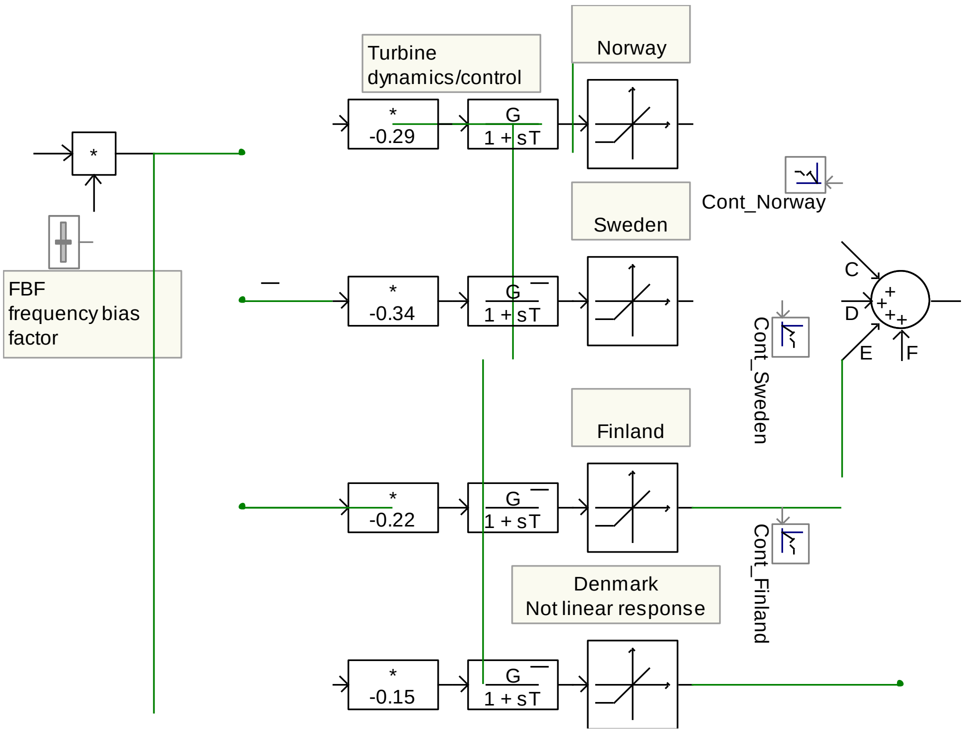

Figure 29 Simulation model used for illustration. The FBF is shared for each TSO in same proportions as reserve obligations. Time constants are according to above table from RAR report [36]. See footnote 23.

In "illustrative" simulations[24] the inertia can be freely adjusted as well as the FBF. The frequency dependency of loads is kept as present practice, 200 MW/Hz. The inertia of loads has considered to be negligible. In these simulations there are no network and the changes in power flows, which will affect the voltage profile and thus loads is not taken into account. It should also be noted that the FBF and inertia are not totally independent of each other. In this

[23] The studies in this report is following the steps in report [36]. In this a time constant for Sweden of 60 s is used, but it is also noted that switch over of parameter setting takes place, which in reality makes the time constant shorter.

[24] Fingrid PSCAD-model tuned in against RAR-model and its analysis result. Only used for this study purpose.

study, the FBF is kept constant independently of total volume of FCR-D. I.e. the changed volume FCR-D will have an impact on the minimum instantaneous frequency level as well as the recovery phase to quasi stationary frequency level (i.e. quasi stationary frequency drop will be the same in the two different scenarios).

The hard limiters limits the control power to obliged power of each TSO.

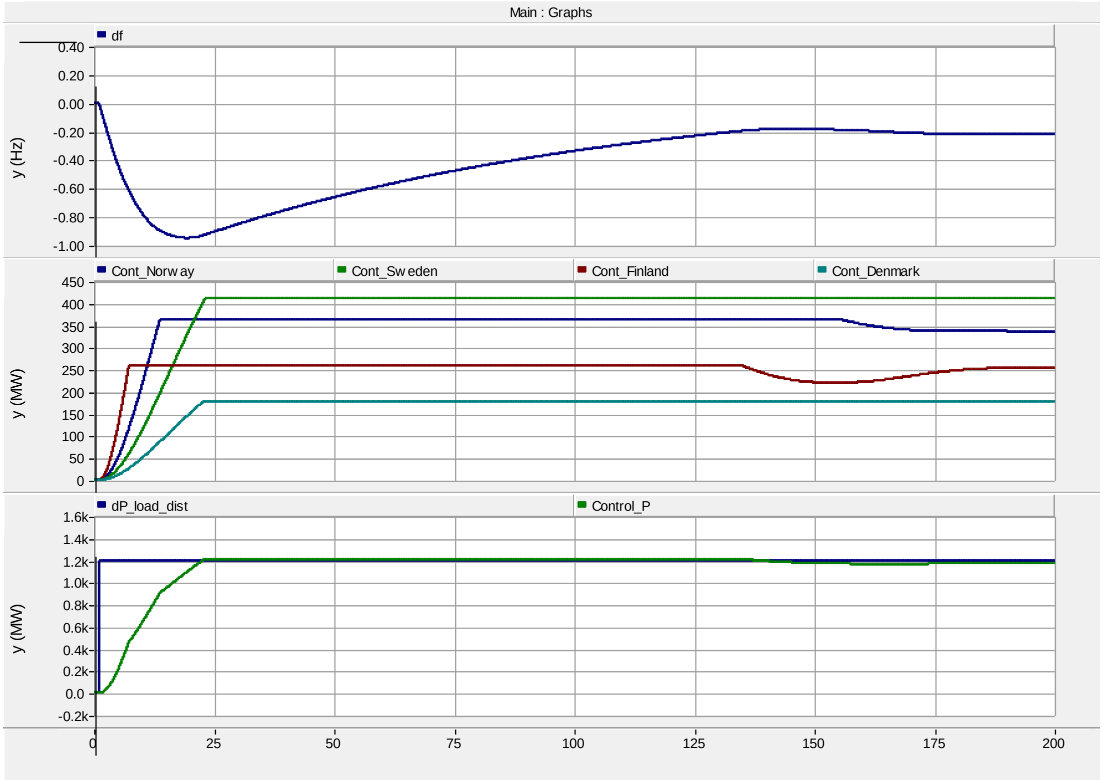

Figure 30 Responses in case of 1200 MW loss of production. From top: Frequency deviation/ Reserve power responses of each TSO / Power trip and total control power response. Inertia 10000MWs/Hz, FBF = 5230 MW/Hz, Control with present time constants according RAR report. See footnote 23.

Illustrative simulations, typical reserves

A similar case as in previous section, but with typical reserves in the NSA according to Table 8 is presented below.

Table 8 The amount of FCR-D provided today (typical figures)

Norway	Sweden	Finland	Denmark	Total
1400 MW	792 MW	259 MW	177 MW	2628 MW

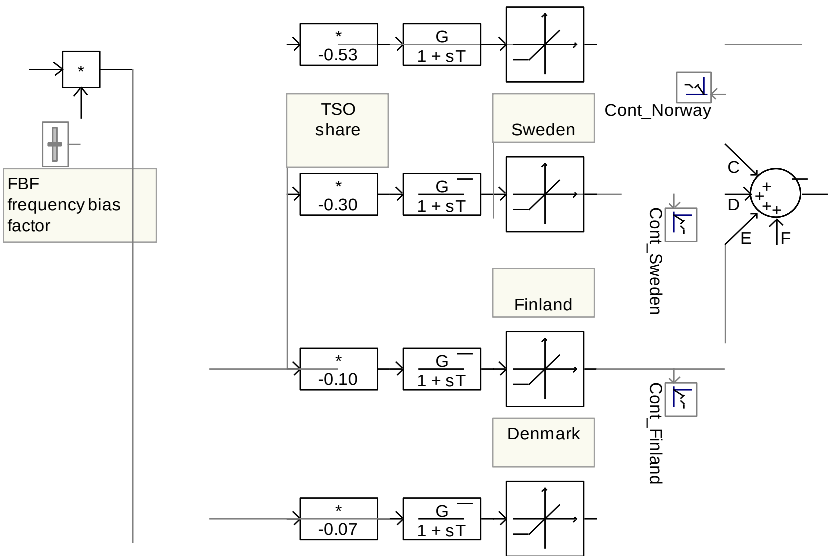

Figure 31 Simulation model used for illustration. The FBF is shared for each TSO in same proportions as amount of reserves. Time constants are according to above table from RAR report. The limiters are not active. See footnote 23.

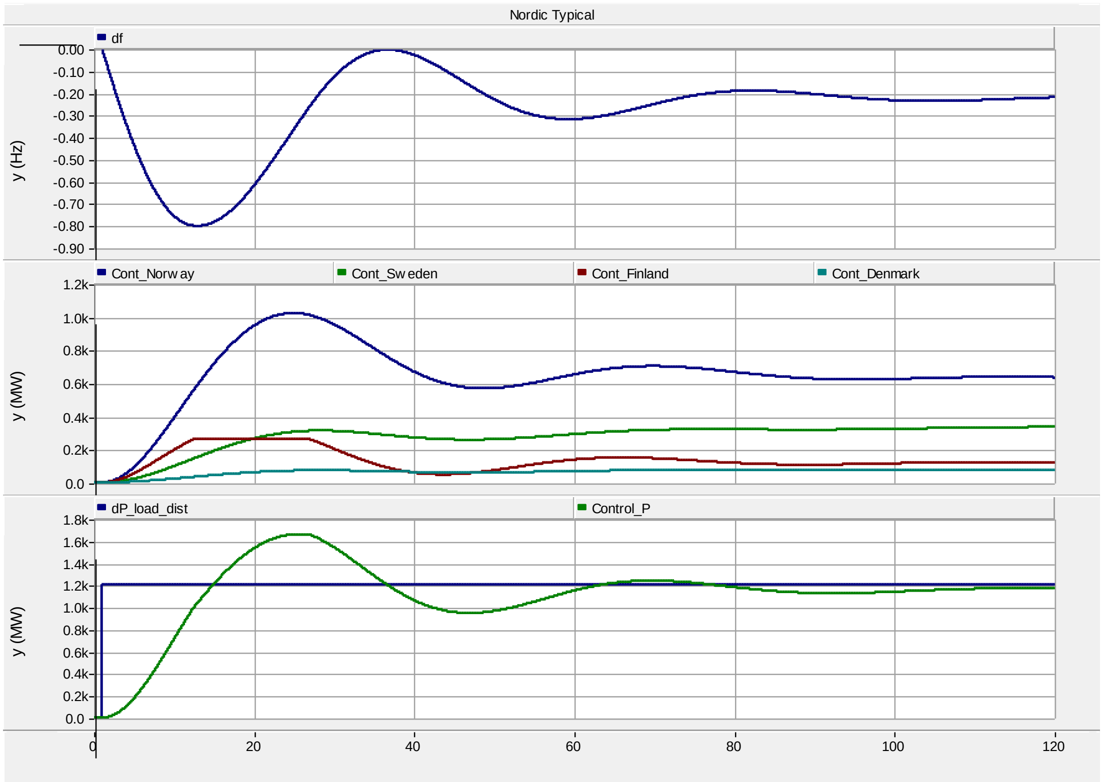

Figure 32 Responses in case of 1200 MW loss of production. From top: Frequency deviation / Reserve power responses of each TSO / Power trip and total control power response. Inertia 10000MWs/Hz, FBF = 5230 MW/Hz, Control with present time constants according RAR report. See footnote 23.

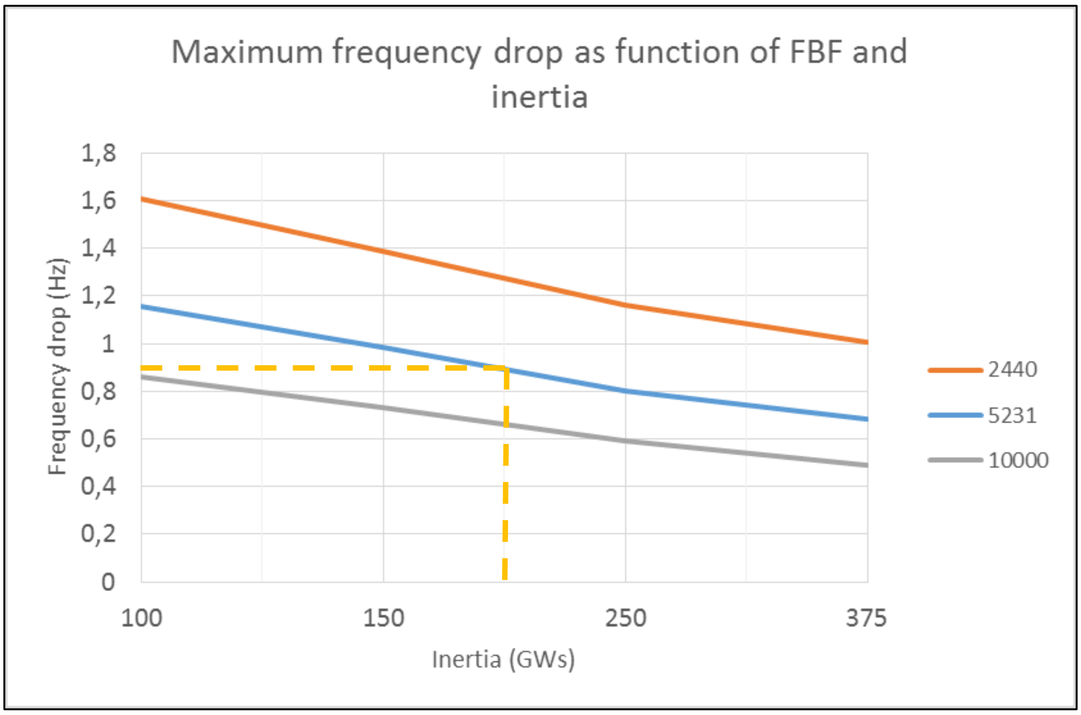

Figure 33 Maximum instantaneous frequency drop (y-axis) vs. inertia (x-axis) and FBF (orange, blue, grey) as parameter. Yellow dashed line represents value in summary of analyses, section 9.4.

9.4 Summary of analyses

The distribution of FBF is not known, but an estimation of inertia distribution for two years is presented in Table 9[25]. The table has been created as follows.

A) The distribution of the production of the Nordic synchronous area has been obtained from the statistics given by NordPool (the values of production is given in the column 'sum').

B) The production has been assumed to consist of certain shares of renewable sources (wind and sun), thermal and hydro power (each given in its own column).

C) It has been assumed that the average inertia constant is 0 for renewable generation, H_T = 5 s for thermal power plants and H_H = 3 s for hydro power.

D) It has been assumed that the average power factor equals 0.9 and that the hydro power plants are operating at a power of 80 % of the maximum power, on the average.

E) The kinetic energy of the Nordic synchronous has then been estimated by the formula

[25] The origin of the table is a Fingrid internal presentation material.

$W_{\mathrm{kin}} = \dfrac{P_{\mathrm{H}} H_{\mathrm{H}}}{0.8 \cdot \cos\phi} + \dfrac{P_{\mathrm{T}} H_{\mathrm{T}}}{\cos\phi}$, where P_H and P_T are the active power produced by hydro and thermal power, respectively. The values of W_{kin} has further been translated to units GWs and given in the column 'inertia'.

Table 9 Estimated inertia distribution in NSA during years 2010 and 2011.

Inertia	Production				CPF	
GWs	sum	wind&sun	thermal	Hydro	2010	2011
110	30 GW	7 GW	10 GW	13 GW	-	-
146	30 GW	-	15 GW	15 GW	86,08 %	92,18 %
194	40 GW	-	20 GW	20 GW	47,90 %	47,33 %
250	52 GW	-	26 GW	26 GW	14,33 %	7,68 %
300	62 GW	-	31 GW	31 GW	0,16 %	0,00 %

The table indicates that median for Inertia is around 190 GWs. The FBF is normally more than 6000 MW/Hz. This suggests that the median instantaneous frequency deviation during Dimensioning Incident would be somewhere around 0.8 - 1.0 Hz (dashed line in Figure 33). This frequency drop is larger compared with historical values in Figure 28. However, a comparison is complicated since both simulations and historical values are vitiated with uncertainties. Factors like load frequency dependency, activated emergency power from HVDC cables, real FBF and real inertia are variables that to some extent are uncertain in one or both of the two cases (simulation vs statistical data).

When looking at Figure 32, the different response of control power before the minimum instantaneous frequency shows reveals a need to harmonize the speed of reserves (or at least making the slow acting reserves act faster).

From Figure 30, showing the responses with only obligatory reserves, it can be seen that if the frequency dependency of loads is less than expected there is an increased risk for collapse.

10. Conclusion

Within this work, the focus has been to study possible quality indices for normal operation and operation outside normal operating band and understand factors, and relationship between these, that affect the quality. Consequences are being described and analysed for different values of quality, but no concrete recommendations are being presented for specific thresholds, target levels etc.

From the historical research, it has been confirmed that frequency quality evaluation is a rather modern topic that wasn't that much considered 20-30 years ago. Earlier, there was no evaluation of time outside normal operating band. Therefore, it has also been difficult to, in detail, compare quality per today with historical values. From samples, it is however reasonable to believe that the quality has been degraded, which can also be seen in the trend curve for the latest 15 years.

The LFC&R [8] defines "frequency quality defining parameters". Per today, several of these parameters are in some way used in the NSA. These are "Standard Frequency Range", "Maximum Instantaneous Frequency Deviation" and "Maximum Steady State Frequency Deviation". Of these, it is only the first one that is associated with a "frequency quality" measure, where the minutes outside normal operating band (or standard frequency range) is measured. The other parameters are to be seen as fixed limits that are not to be violated. Measurement of frequency drop will give a good indication of the system state. However, that is not seen as a quality index for frequency, instead it is a useful measurement for post-incident analysis for verification of amount of inertia and FBF in the system.

Comparing frequency quality indices with other synchronous areas shows that the Nordic present way of following frequency is comparable. There are synchronous areas were the allowed time outside normal operation is less compared with the Nordic, and other areas have a larger allowed time outside normal operation. However, it is of importance to also notice that the size of band for normal operation also differ, which makes a comparison difficult.

The band for normal operation is per today ±100 mHz, which also is in line with the default value in the LFC&R code. From the historical research it was found out that this particular limit was set due to two reasons; 1) it was a reasonable band of operation for units equipped with electrohydraulic governors and 3) it would result in an increased margin for activation of FCR-D.

For evaluating the frequency quality related to minutes outside normal operating band, the resolution of frequency data can be lower compared with measuring frequency drop, In the LFC&R code there is a requirement that measurement period should be equal or shorten than 10 s. Comparing the measurement method for counting minutes outside normal operating band used per today, the method given in the LFC&R code would give approximately the same annual number of minutes outside normal operating band as achieved with the present SvK-method of measuring. However, the relative difference between two different methods can much higher on short time, for instance when comparing weekly values. Therefore, it is recommended to improve the measurement method so that statistics are based on continuous measurements using all 10 s average values in the frequency measurement.

A follow up on the frequency distribution curve (including standard deviation value) gives additional, valuable information compared with just specifying "minutes outside", in that sense that the characteristics of the "minutes outside" is actually presented. As an addition to this, or alternatively, also the number and duration of occasions outside a certain frequency band, other than the normal operating band, could be followed. The key questions are what the operator sitting in the control room needs in order to help maintaining sufficiently good frequency quality and what kind of tools the TSOs need for evaluating the reserves and market mechanisms.

Looking at the consequences of larger or smaller amount of minutes outside normal operating band, it has an impact on the probability of going below a certain lowest accepted frequency level during a Dimensioning Incident. A higher number of minutes outside normal operating band means a higher probability that the frequency is already under normal operating band when a major incident occurs, and consequently leads to a higher probability of going under a certain minimum instantaneous frequency. The probability of going under the minimum instantaneous frequency however depends also on other things like amount of FCR and inertia. Going below instantaneous minimum frequency level will result in a risk of activation of load shedding schemes, which is to be considered as entering an emergency state. Trip of production and HVDC connections requires very large frequency deviations.

Recommendations for further work

The following recommendations for further work is given

1. Frequency quality versus operational risks

As seen in the simplified study in this work, the probability of entering emergency state after a Dimensioning Incident increases only little when the number of minutes outside normal operating band increases. It is recommended that further work shall be performed with focus on defining what acceptable risk the system can be operated with considering frequency quality level, and thereby finding reasonable limits for operation, both for normal state and alert state. The work shall also consider factors that today are known with a great deal of uncertainty. This work needs to be coordinated with the current project "Revision of Technical Specification for Frequency Containment Process".

2. Additional frequency quality parameters

It is recommended that additional frequency quality indices are defined to have more detailed history for coming evaluation of reserves and revisions of requirements. This could for example be number of events outside normal operating band, durations of frequency deviations outside normal operating band, how to evaluate outages to check the relations between all elements like inertia, FBF, steady state frequency deviation, in relation to instantaneous frequency deviation. Index for amount of oscillations in the frequency has not been covered within this work, but it is suggested to be included as one of the additional indices.

3. Frequency and voltage dependency of loads

In addition to the development of different indices, there is also a need to have better knowledge of what the frequency dependency of load in the system is, both in normal operation and also after outages including the different reactions to the geographical origin of the outage.

4. HVDC-interconnections correlation to frequency quality

The HVDC-interconnections is well known for affecting frequency quality goals but how much it affects is important to investigate. It is also recommended to investigate how to minimize the HVDC interconnections impacts of frequency quality and power system security.

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Annex A – LFC&R – frequency quality target parameters Article 19

The parameters below were decided by RGN [19.11.2013] who intended that a second set of parameters shall be defined that are more onerous and that these shall be used in the Nordic SOA.

Table 10 Frequency Quality Defining Parameters of the Synchronous Areas

	CE	GB	IRE	NE
Standard Frequency Range	±50 mHz	±200 mHz	±200 mHz	±100 mHz
Maximum Instantaneous Frequency Deviation	800 mHz	800 mHz	1000 mHz	1000 mHz
Maximum Steady State" Frequency Deviation	200 mHz	500 mHz	500 mHz	500 mHz
Time to Recover Frequency	not used	1 minute	1 minute	not used
Frequency Recovery Range	not used	±500 mHz	±500 mHz	not used
Time to Restore Frequency	15 minutes	10 minutes	20 minutes	15 minutes
Frequency Restoration Range	not used	±200 mHz	±200 mHz	±100 mHz
Alert State Trigger Time	5 minutes	10 minutes	10 minutes	5 minutes

The Frequency Quality Target Parameter shall be the target maximum number of minutes outside the Standard Frequency Range per year per Synchronous Area, and its default value per Synchronous Area shall be the value given in Table 10.

Table 11 Target level for Maximum number of minutes outside the Standard Frequency Range

	CE	GB	IRE	NE
Maximum number of minutes outside the Standard Frequency Range	15000	15000	10500	15000

Annex B – Synchronous area comparison

	Nordic	CE (Former UCTE)	Great Britain	Russia	Western Interconnection	Eastern Interconnection	ERCOT	Quebec	China	Chile	Australia
Nominal freq (Hz)	50	50	50	50	60	60	60	60	50	50	50
Normal band (Hz)	49.9-50.1	49.95-50.05	49.8-50.2	49.95-50.05	*59.856-60.144*	*59.95-60.05*			49.8-50.2	49.8-50.2	49.85-50.15
Allowed annual minutes outside normal band	10 000 min/year ***(in the Grid Code LFCR the default value 15000 minutes outside the normal band is given, but that value has not been abreed on by the Nordic TSOs)***		2250 min/year ***(in the Grid Code LFCR the target value 15000 minutes outside the normal band is given)***	26300 min/year					10500 min/year	5250-15800 min/year	5260 min/year
Allowed percentage of time outside normal band	1.9 % (2.9 % based on the default value of NC LFCR)		0,40 %	5 %					2 %	1-3 %	1 %
Allowed standard deviation (Hz)	0,042		0,07	0,026			0,37037037		0,086	0.078 - 0.092	0,058
Allowed time deviation	+/- 30 sec	+/- 30 sec	+/- 30 sec (should be recovered to 0 by the end of the day)	+/- 20 sec normal (+/- 30 sec max)							+/- 5 sec - +/- 15 sec
Frequency Bias Factor min requirement	6000 MW/Hz	15 000 MW/Hz	For 1000 MW loss at 50 GW demand: 450 MW primary response, for 1320 MW loss att 50 GW load 400 MW		*14820 MW/ Hz*	*27600 MW/ Hz*	*6500 MW/ Hz*	*12000 MW/ Hz*			
Frequency Bias Factor normal level	10000 MW/Hz	19 500 MW/Hz									
Primary reserves activation time	50 % in 5 sec 50-100 % in 30 sec	50 % in 15 sec 50-100 % in 30 sec	100 % in 10 sec	50 % in 15 sec, 50-100 % in 30 sec							
Minimum instantaneous freq (Hz)	49.0	49.2	49.5 for loss of production <300 MW, 49.2 for loss of production <1320 MW	49.2						48.3	
Quasi-steady-state freq (Hz)	49.5	49.8/50.2	49.5/50.5	49.8/50.2							
Time correction method	Manual (is also possible with FRR-A, altering freq target set point)	Automatic using ACE	Altering target freq of the generators	Automatic using ACE							

[6], [2], [8], [45], [46]

Annex C – Terms of reference

In the terms of reference the following aspects effecting frequency quality should be included in the work:

- Minutes outside the band
- Frequency after disturbances
- Frequency oscillations
- Time deviation
- Frequency containment reserves (FCR) means the Operational Reserves activated automatically to contain System Frequency after the occurrence of an imbalance
    - Including governor settings in general
- Frequency restoration reserves (FRR)
- Inertia
- Tertiary reserves
- Load profile
- Power plant and HVDC operation
- Quarterly adjustment
- What is included in the grid code

Annex D – Automatic Load shedding schemes

The figures in this annex visualize the limiting frequency levels created by accepted area of operation for production units and load shedding levels. The x-axis represent the time duration for certain frequency levels.

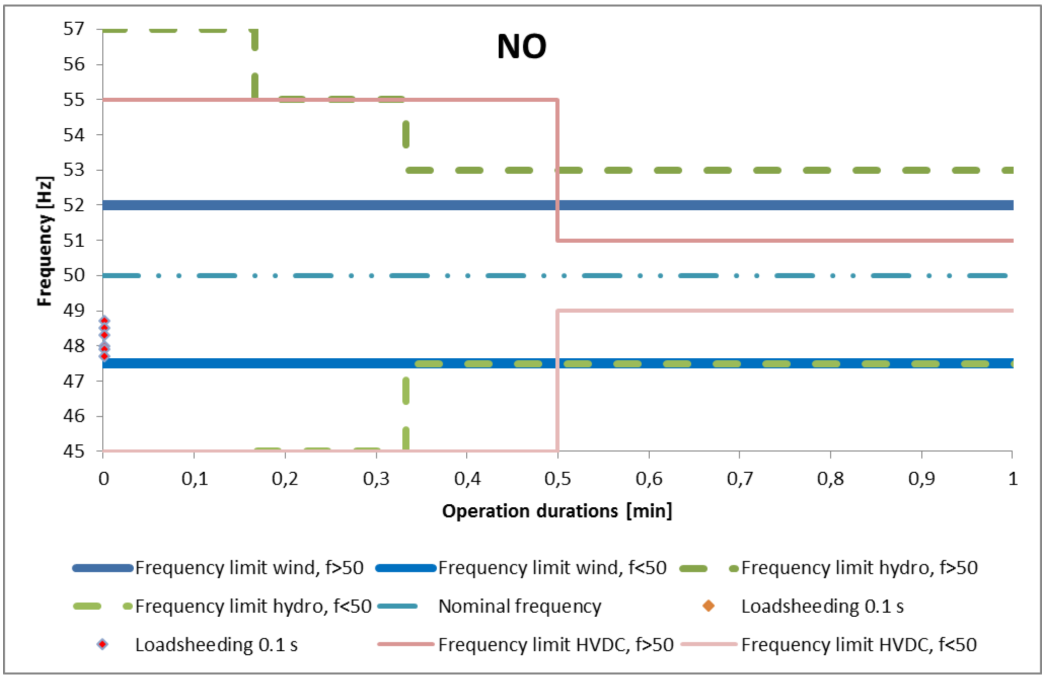

Figure 34 Frequency minimum levels, time scale 0-1 minutes, Norway.

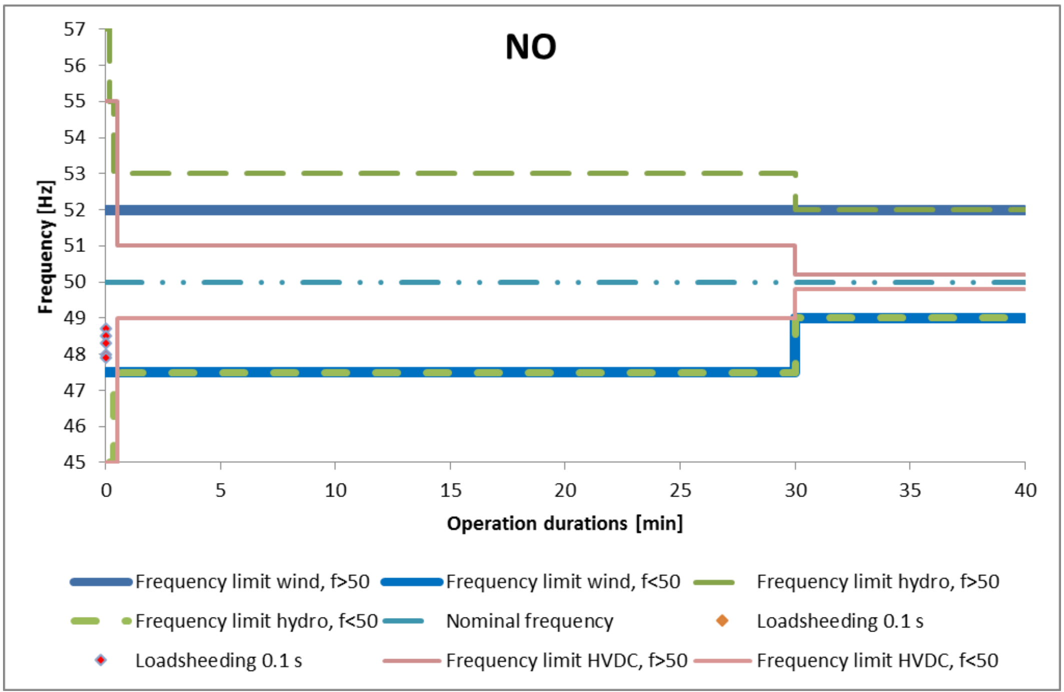

Figure 35 Frequency minimum levels, time scale 0-40 minutes, Norway.

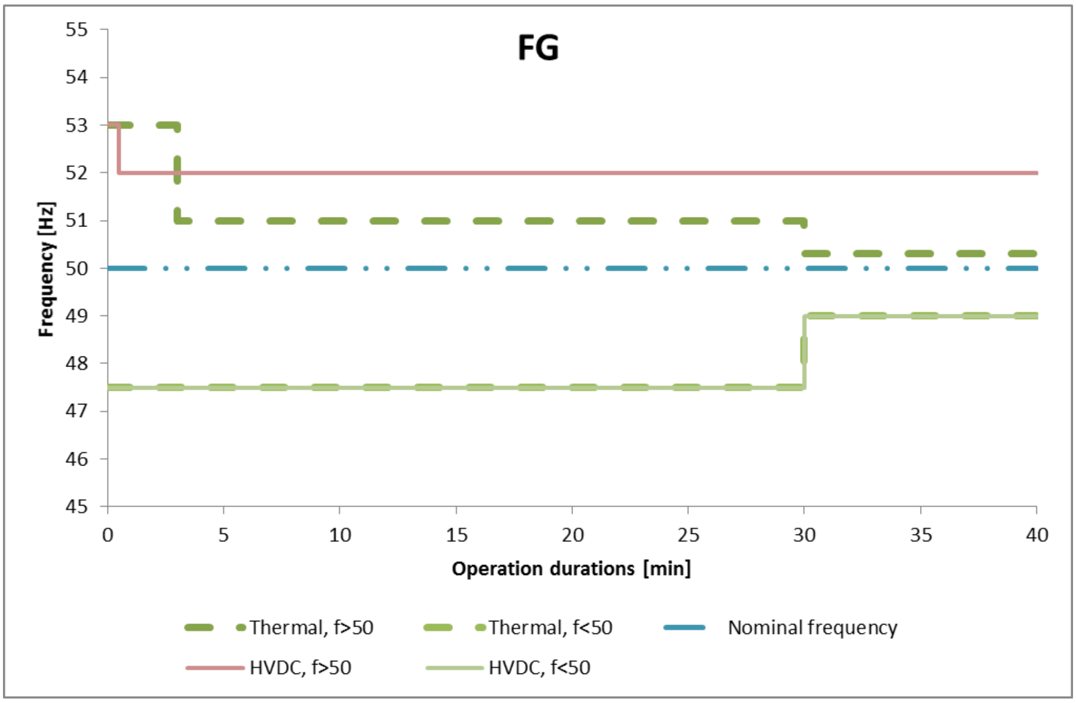

Figure 36 Frequency minimum levels, time scale 0-40 minutes, Finland.

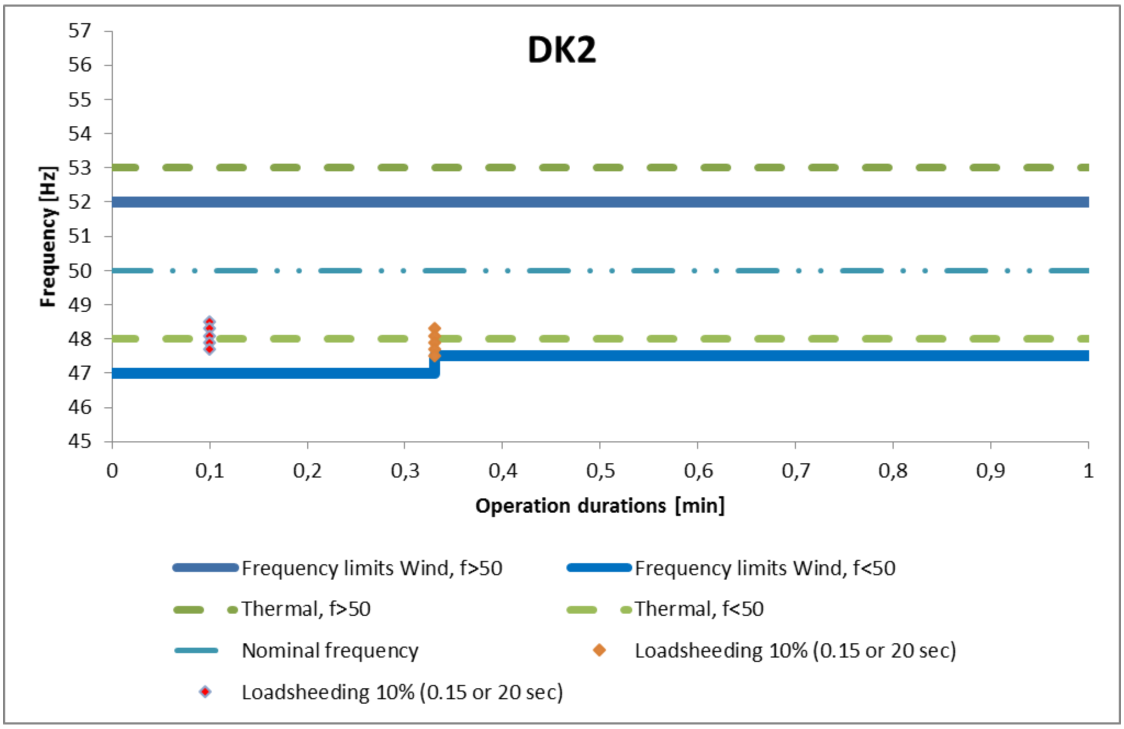

Figure 37 Frequency minimum levels, time scale 0-1 minutes, Denmark (DK2).

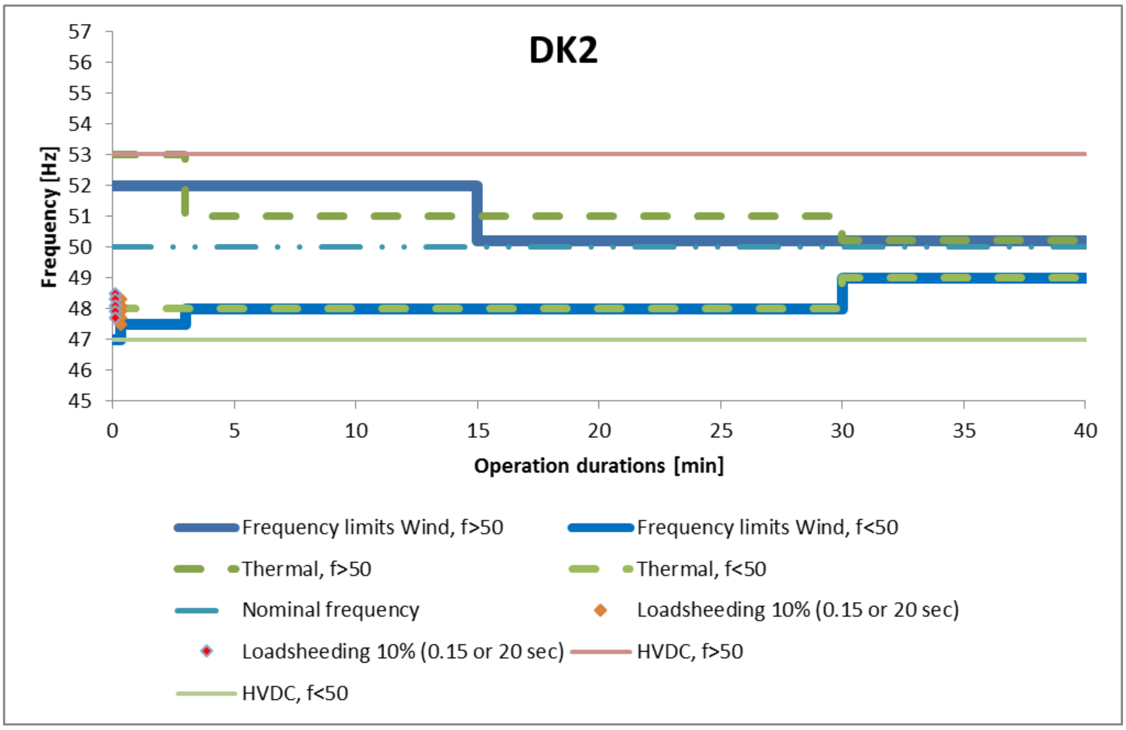

Figure 38 Frequency minimum levels, time scale 0-40 minutes, Denmark (DK2).

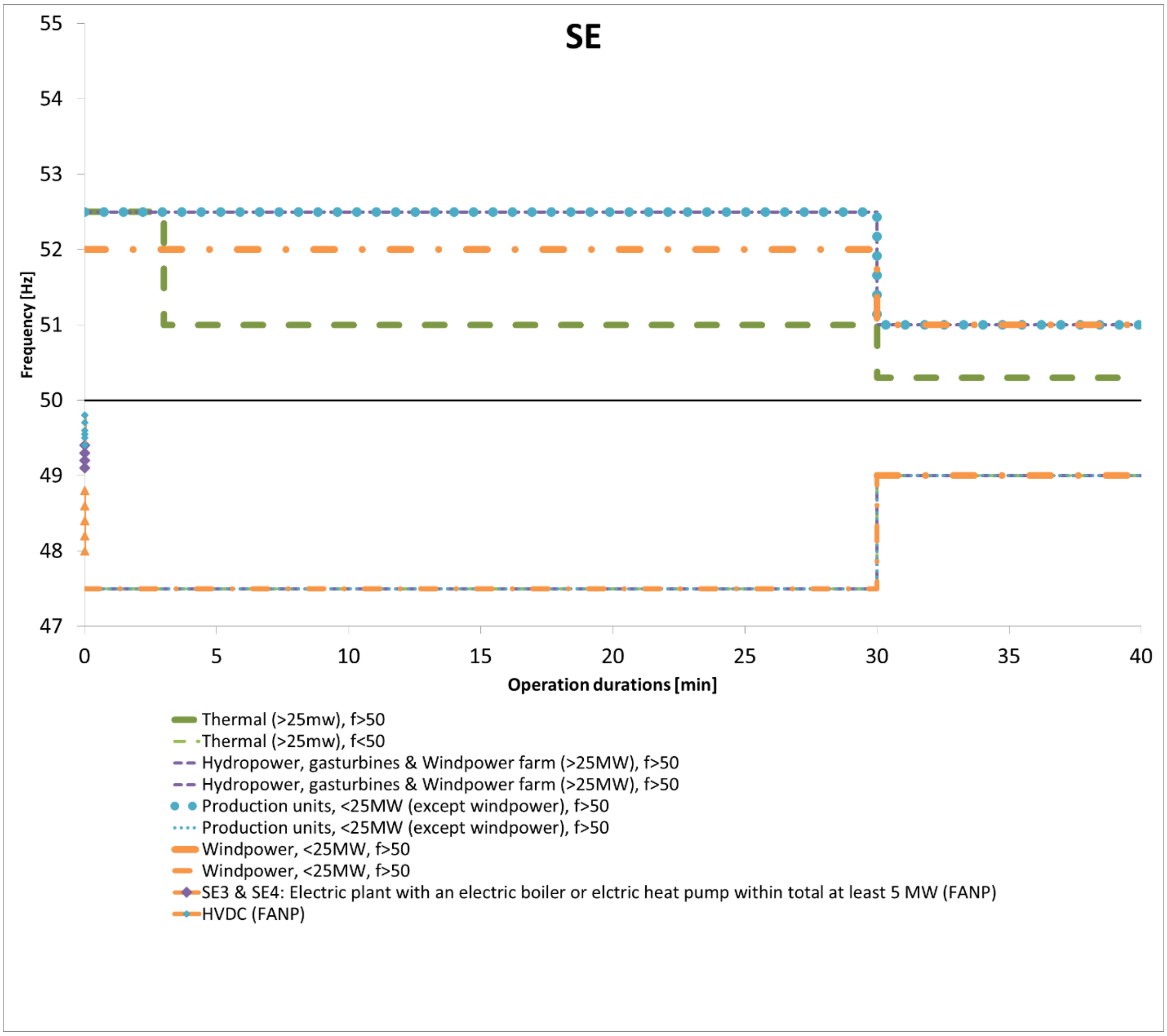

Figure 39 Frequency minimum levels, time scale 0-40 minutes, Sweden.

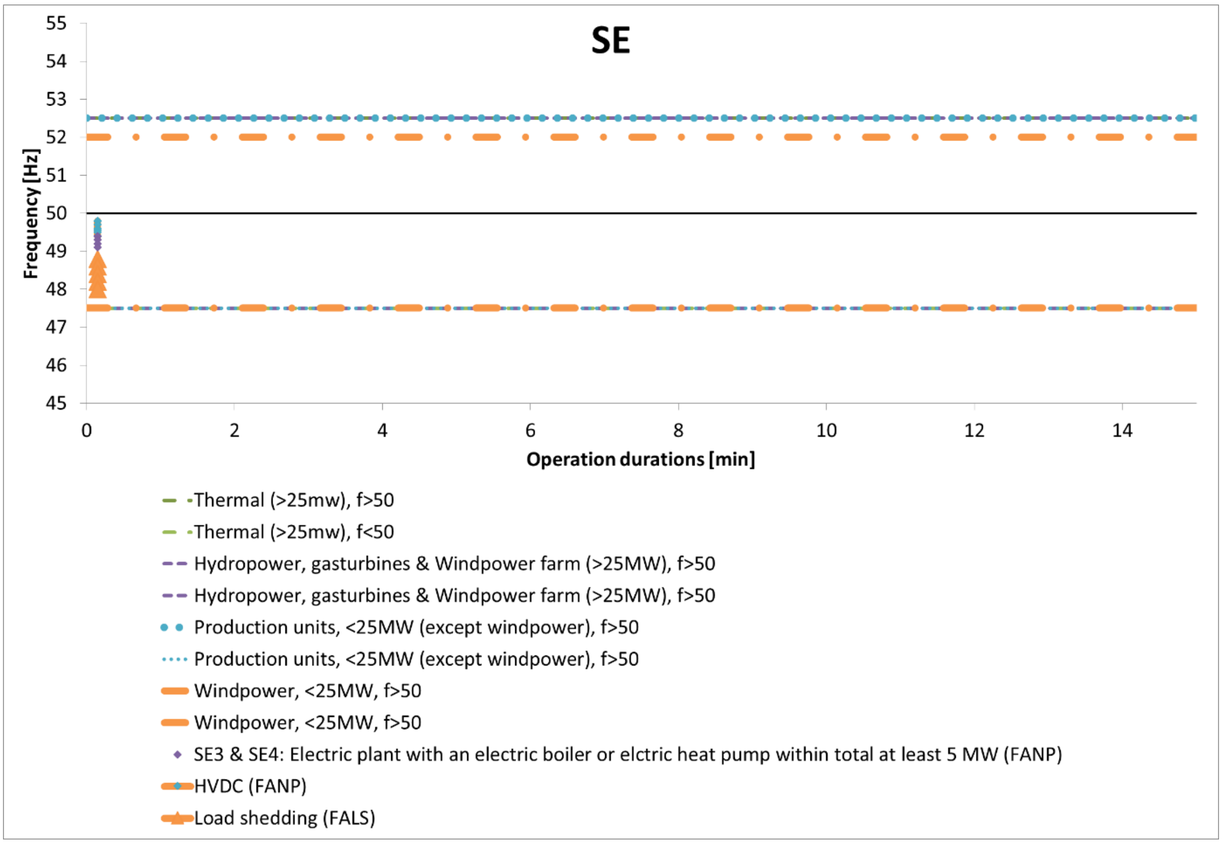

Figure 40 Frequency minimum levels, time scale 0-14 minutes, Sweden.