Frequency Quality, phase 2

Project Report - Version 1.2 -

NAG

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Executive Summary

Frequency variation in the power system is caused by different types of imbalances between production and consumption with different time frames: sudden imbalance caused by equipment failure, stochastic imbalance, deterministic imbalance (especially during hour shifts), imbalance due to forecast errors, etc. Frequency quality is dependent on how these imbalances with different causes can be handled. A crucial target is to keep the frequency above such level where the automatic Under Frequency Load Shedding (UFLS) is activated.

This report presents a probabilistic methodology that can be applied to estimate the risk that UFLS is activated (UFLS risk). The methodology uses the parameters that have significant influence on the UFLS risk as an input: Inertia, FCR-D response time and volume, Emergency Power (EPC) provided by HVDC links, self-regulation of loads, size and probability of disturbances, frequency variation (minutes outside normal frequency band - MoNB), threshold of first stage of UFLS. The methodology estimates the UFLS risk for a single hour or even minute, but can also be used for estimating figures of UFLS risk over a complete year, both historical and in the future.

This report suggests a target for UFLS risk of ‘less than one UFLS event in 40 years’ in order to meet the requirements of the Guideline on System Operation. The probabilistic methodology can be used for determining a relationship between forecasted level of inertia in the power system and the required MoNB to meet this UFLS target. Since MoNB can be influenced by FCR-N and aFRR, this relationship can be used for planning the purchase of FCR-N and aFRR based on the forecasted level of inertia.

The socio economic cost for UFLS risk has been estimated. However, the determined optimal UFLS risk has a limited accuracy since some of the currently available input parameters have a limited accuracy. Nevertheless, the calculations can provide some insight in the orders of magnitude.

Sensitivity studies were performed in order to see the impact of different parameters on the UFLS risk. Self-regulation, EPC and FCR-D provided by directly disconnectable load have a major influence. FQ2 recommends exploring the possibilities of using EPC and FCR-D by load.

This report also proposes a frequency quality reporting framework and defines new indices for steady state frequency, damping of frequency after a disturbance and deterministic frequency deviation. The implementation of an automatized on-line reporting tool for some indices is suggested, but as a first step a report every three month as required in Guideline on System Operation can be issued.

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Abbreviations and symbols

Abbreviations

aFRR	automatic Frequency Restoration Reserves
DSO	Distribution System Operator
ENTSO-E	European network of transmission system operators for electricity
EPC	Emergency Power Control
FBF	Frequency Bias Factor
FCP	Frequency Containment Process
FCR	Frequency Containment Reserve
FCR-D	Frequency Containment Reserve for Disturbances
FCR-N	Frequency Containment Reserve for Normal operation
FRP	Frequency Restoration Process
FQ2	Frequency Quality project, phase 2
GL SO	Guideline on System Operation
HVDC	High Voltage Direct Current
MoNB	Minutes outside the Normal Band or Standard Frequency Range of 49.90-50.10Hz
NAG	Nordic Analysis Group
NOD	Nordic Operations Development group
NOG	Nordic Operations Group
NOIS	Nordic Operator Information System
PMU	Phasor Measurement Unit
RGN	Regional Group Nordic
RAR	Requirements for Automatic Reserves project
ROCOF	Rate-of-change-of-frequency
SPS	System protection scheme
TSO	Transmission System Operator
UFLS	Under Frequency Load Shedding

Symbols

E_k	Kinetic energy
f	Frequency
f_{extreme}	The minimum or maximum instantaneous frequency
f_{nadir}	The minimum instantaneous frequency
f_{n}	Nominal frequency
f_0	Frequency at the start of the disturbance
P	Active power
t_{extreme}	The time the frequency reaches f_{extreme}
t_{start}	Start time of the disturbance

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1 Introduction

1.1 Background

Frequency variation in power system is caused by different types of imbalances between production and consumption with different time frames: sudden imbalance caused by failure, stochastic imbalance, deterministic imbalance (especially during hour shifts), imbalance due to forecast errors, etc. Frequency quality is dependent on how these imbalances with different causes can be handled. Main target is to keep the frequency above such level where the automatic Under Frequency Load Shedding (UFLS) is activated.

The Nordic analysis group (NAG) completed several projects related to frequency quality. The Frequency Quality project, phase 1 gathered information on the historical background on different aspects of frequency quality[1]. Furthermore, the 'Future System Inertia 1' project studied the inertia and influence of inertia on frequency quality[2]. Their project reports form the starting point for the study which is described in this report.

1.2 Objective

The main objective of the Frequency Quality 2 project (FQ2) was to prepare a framework in which the target level for Security of Supply with respect to frequency quality can be established. Security of Supply can be expressed in the number of years between events with automatic UFLS. Based on the target level, the Nordic TSOs may decide on the required level of frequency quality and the required amounts of reserves and other measures.

Another objective for the FQ2 project was to define the frequency indices that are followed up in Nordic TSOs. These indices are needed in order to be able to follow if the frequency fulfils the frequency quality targets. Part of the indices do not have some defined target value but instead give a view on the situation to be compared to historical values.

1.3 Related projects

Simultaneously to the study described in this report, NAG runs several related projects. Firstly, the 'Future System Inertia 2' project with focus on finding the tools to keep the frequency above 49.0Hz in order to avoid UFLS at any expected level of inertia. Secondly, the FCP project prepares the new technical requirements for FCR-N and FCR-D and thirdly, the 'Load shedding project' studies Under Frequency Load Shedding/Over Frequency Control Schedule.

Results of the FQ2 project give input related to the drafting work of the new Nordic System Operation Agreement, especially to the annex on Load-Frequency Control And Reserves (LFCR).

1.4 Focus of the project

The FQ2 project focused on the frequency range between 49.0 and 51.0Hz and the effect that excursions below 49.0Hz may result in automatic Under Frequency Load Shedding (UFLS). UFLS and Over Frequency Control Schedule are addressed in the Load shedding project.

1.5 Note/disclaimer

The first priority of the FQ2 project team was model development and consequently, the quality of the input data has not been prioritised. This includes the use of the so called RaR model of the Nordic FCR, that has been developed in 2011 and still reflects the best estimate of that time for the 2011 situation. This may affect the absolute quantitative results in this report and therefore need to be considered as examples or indications of the order of magnitude. However, the FQ2 project team has confidence that the conclusions presented in chapter 8 are not significantly affected.

[1] NAG frequency quality report, version 2.0, April 2015

[2] Nordic Report Future system inertia, 2015

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1.6 Report set-up

The report starts with a description of the objective of frequency quality in chapter 2. Chapter 3 defines a framework for frequency quality. Chapter 4 describes the parameters that affect Under Frequency Load Shedding (UFLS) Risk. In chapter 5 a probabilistic methodology for determination of UFLS risk is described, including the results and a discussion on the results. The application of this methodology is discussed in chapter 6. Chapter 7 discussed a framework on reporting. Conclusions and recommendations are described in chapter 8.

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2 Objective of frequency quality

2.1 Main objective maintaining frequency quality

In order to maintain a good security of supply level, TSOs shall maintain the balance in the synchronous transmission system. *Frequency quality* is a measure on how well the TSOs succeed in doing this. In power systems with a higher frequency quality, imbalances – caused by e.g. a trip of a generation plant or an HVDC link – will have a lower probability to result in imbalances that need to be mitigated by automatic Under Frequency Load Shedding (UFLS) or that result in a system blackout.

It shall be noted that the term frequency quality is also frequently used for minutes outside the normal frequency range. In this report the term frequency quality is used in line with the Guideline on System Operation (GL SO) which implicitly refer to the description in the previous paragraph.

The high level objective of *maintaining frequency quality* is to limit the risk of supply interruptions caused by imbalances to acceptable levels.

The TSOs can maintain the frequency quality by:

1. Keeping the *frequency* at times without large disturbances close enough to 50Hz;
2. Arrange sufficient and accurate measures (reserves, inertia, emergency measures) to limit the *frequency change* after an incident in order to keep frequency above a certain *minimum frequency*;
3. Maintaining *sufficient margin* for inaccuracies to limit the probability of UFLS;
4. Arrange *emergency measures* such as UFLS to limit the impact of large events that are not addressed by normal means.

In this document, frequency quality refers to the quality that shall be maintained to keep the required Security of Supply (SoS) level with respect to frequency. The measure for the SoS level that is applied in this document is UFLS risk, expressed in expected number of years between two events of UFLS, e.g. one event of UFLS in 40 years.

Two important notes:

- There is very little practical experience with the Nordic system for frequencies below 49.5Hz. According to the rules, requirements and specifications, connected production plant, load and network should continue working properly down to the first level of Under Frequency Load Shedding (at 48.8Hz). However, this has never been tested or experienced on a system scale;
- The parameters that affect frequency quality constantly change and result in a security of supply that is different for every hour. Maintaining frequency quality may therefore have different interpretations which include 'maintaining the same security of supply for every hour' and 'maintaining an average security of supply for a period, e.g. a year'.

2.2 Other objectives maintaining frequency quality[3]

2.2.1 Compliance with standards for network user's appliances

The requirements in the European Generator Connection Code and the Demand Connection Code[4] describe that if the frequency is in between 49.0 and 51.0Hz, demand and generation shall be capable of remaining connected to the network and operating for unlimited time. If the frequency is outside this range, but inside 47.5-51.5Hz, demand and generation shall be capable of remaining connected to the network and operating for at least 30 minutes.

European Standard EN 50160 requires that - under normal operating conditions - the frequency shall be within 49.5-50.5Hz for 95% of time[5]. Currently, the Nordic frequency quality is far better than required by this standard since excursions outside this frequency band are very rare and usually very short[6].

2.2.2 Compliance with design for network equipment of TSO and DSOs

Network equipment of TSOs and DSOs shall be able to operate safely and securely within the frequency range in which the power system is operated. Typically, power transformers may be vulnerable to a combination of high voltage and low frequency. In this situation, (over)flux may create intolerable heating of the core. Transformer design needs to take this into account.

2.3 System States – Alert State Trigger Time

Article 18 of the System Operation Guideline defines the system states, which are defined as *the operational state of the transmission system in relation to the operational security limits which can be normal state, alert state, emergency state, blackout state and restoration state.*

This section 2.3 describes these system states in relation to frequency. In addition, the section will discuss the value for the alert state trigger time which the Nordic TSOs are allowed to define differently from the value of 5 minutes that has been defined in the GL SO[7]. Section 2.3.1 starts with a proposed interpretation of 'alert state trigger time' and 'steady state frequency'.

2.3.1 Definitions and proposed interpretation

2.3.1.1 Steady State frequency

According to article 18 of the GL SO, alert state is triggered if the *steady state frequency* is outside a specified band for a certain time. The same GL SO define *steady state frequency deviation* (GL SO art. 3(157)) as the absolute value of frequency deviation after occurrence of an imbalance, *once the system frequency has been stabilised.* Hence, article 18 seems to assume that the *steady state frequency* is continuously changing, while article 3 suggests that for each disturbance, there is only one value of *steady state frequency*. FQ2 therefore concludes that the definition in article 3 cannot be applied to article 18.

As an alternative, FQ2 proposes to use the *rolling average of the previous 60s period* as a proxy for the *steady state frequency* in article 18. The main argument for choosing the parameter of 60s is the time period of the 60s oscillations. Since these oscillations may change over the years, this parameter shall be reviewed by the

[3] Time deviation control is not part of the scope of this Frequency Quality, phase 2 project. Therefore it is not described in this chapter. However, the aggregated frequency deviation determines the time deviation.
[4] Article 12
[5] To be more precise: based on 10s measurement intervals monitored over 1 week.
[6] According to Fingrid's F-Report (report Frequency quality analysis for year 2015, Fingrid, 16.8.2016) between 2008 and 2015 on average 1 event per year with a duration of not more than 10.8s.
[7] GL SO, Annex III, table 1

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Nordic TSOs regularly, and especially when the new FCR requirements have been implemented. Section 3.4 provides the background behind this proxy.

2.3.1.1 Alert State trigger time

The 'alert state trigger time' is defined as *'the time before alert state becomes active'* (GL SO art. 3(98)). Since the *'time before'* does have a starting point, FQ2 proposes to define the starting point as the time of the disturbance: *Alert state trigger time means the time that has elapsed after the disturbance and during which the average system frequency deviation calculated over the previous 60s continuously exceeded 50% of the maximum steady state frequency deviation (250mHz).*

2.3.1.2 Definition of System States in relation to frequency

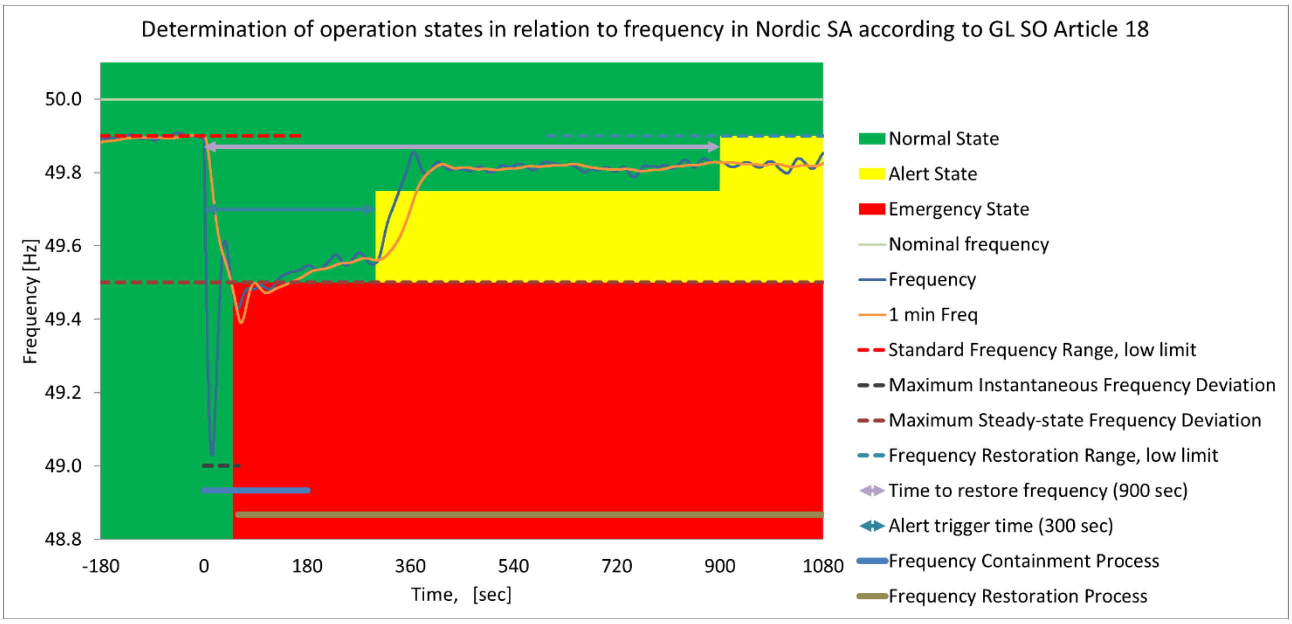

Figure 1: Graphical interpretation of System States as specified in article 18 of the GL SO. Note that the system states are the same on the over frequency side.

Figure 1 shows a summary of the definition of the different systems states in article 18, including the interpretations and the proxy for steady state frequency discussed above:

- Normal state: *rolling average frequency deviation of the previous 60s period* is:
  - within the standard frequency range (±100mHz); or
  - is not larger than the maximum steady state frequency deviation (±500mHz) and the system frequency limits established for the alert state are not fulfilled (±250mHz for more than 5 minutes).
- Alert state: *rolling average frequency deviation of the previous 60s period*[8]:
  - Continuously exceeded 50% of the maximum steady state frequency deviation (±250mHz) for a time period longer than the alert state trigger time (5 minutes); or
  - Continuously exceeded the standard frequency range (±100mHz) for a time period longer than time to restore frequency (15 minute).
- Emergency state: when the frequency does not meet the criteria for the normal state and for the alert state defined above.

[8] The alert state can also be triggered by a reduction of the TSO's reserve capacity

2.3.2 Impact of 'Alert State' and 'Alert State Trigger Time'

The definition of 'Alert State' and setting the 'Alert State Trigger Time' will have impact on the following regulations in the GL SO:

- The time and state of the system at which the synchronous area monitor will need to inform the other TSOs that the system is in Alert State (GL SO art. 152(3));
- The time and state of the system at which the 'common rules' (GL SO art. 152(6)) and 'operational procedures' (GL SO art. 152(10)) for the alert state will become active. These rules and procedures shall be defined by the TSOs;
- The time and state of the system at which the TSOs have the right to require changes in the active power production or consumption of power generating modules or demand units in order to reduce or to remove the violation of the requirements concerning active power reserve (GL SO art. 152(11));
- GL SO art. 156(9-10) defines the minimum activation period to be ensured by FCR providers: 'As of triggering the Alert State and during the alert state, each FCR provider shall ensure that its FCR providing units or groups with limited energy reservoirs are able to fully activate FCR continuously for a time period to be defined.' 'This period shall not be greater than 30 or smaller than 15 minutes.' Alert State Trigger Time determines after what time this functionality requirement for FCR becomes active. Note that this functionality requirement is only valid for Alert State.

2.3.3 Historical time in alert state

During the period 2008 – 2015, 'alert state' would have been triggered only few times and only because the absolute *rolling average frequency deviation of the previous 60s period* was larger than 100mHz for more than 15 minutes. The 'alert state' would have never been triggered on the condition that the absolute *rolling average frequency deviation of the previous 60s period* was larger than 250mHz for more than 5 minutes.

2.3.4 Alert State Trigger Time

The alert state trigger time is defined by the GL SO to 5 minutes[7]. However, according to the GL SO, Nordic TSOs shall have the right to propose alternative values in the synchronous area operational agreement[9].

The FQ2 group considers that it will *not* be very meaningful for the dispatchers to wait for 5 minutes until they will start responding to a disturbance[10]. However, there can be a need for a common Nordic procedure that shall be activated after the first actions of the dispatchers. The optimal Alert State Trigger Time depends on the measures, but the defined 5 minutes seems to be realistic. This is rather an issue for the Nordic operational groups (NOG, NOD) than for a project under the umbrella of the Nordic Analysis Group.

[9] GL SO article 127(6)

[10] Automatic actions – such as starting-up the gas turbines in Sweden - start within seconds in order to be available in 5 to 15 minutes

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3 Framework for Frequency Quality Parameters

3.1 Overview of frequency quality defining parameters

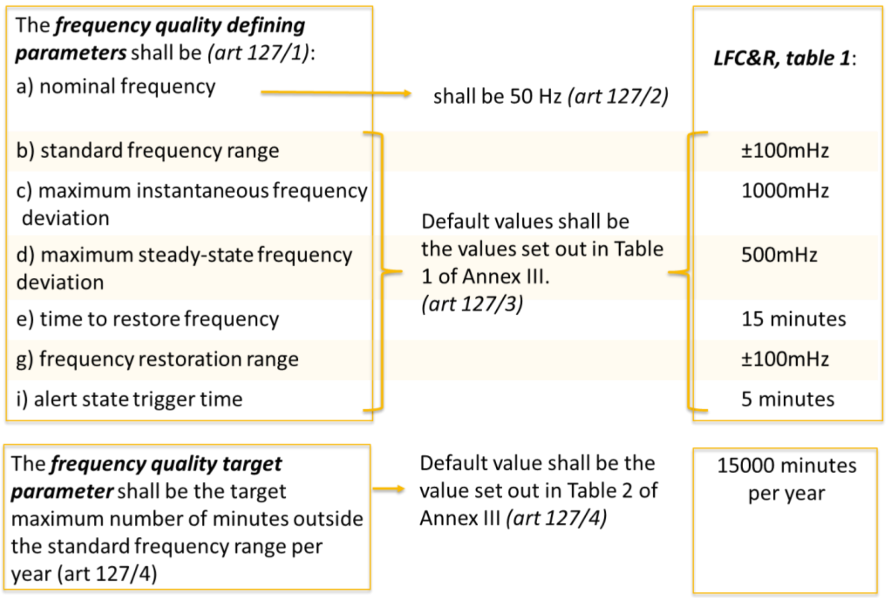

Figure 2: Overview of 'frequency quality defining parameters' and the 'frequency quality target parameter' as mentioned in the GL SO.

The left hand side of Figure 2 shows the frequency quality defining parameters and frequency quality target parameter that have been described in the European Guideline on System Operation (GL SO). The right hand side of the figure shows that a value has been assigned to these parameters. The values of the frequency quality defining parameters a) to g) shall be interpreted as legally binding minimum requirements. Consequently, the TSOs may only decide on applying stricter standards[11]. GL SO 127 allows that all TSOs of the Nordic synchronous area shall have the right to propose different values for the alert state trigger time (see section 2.3) and the maximum number of minutes outside the standard frequency range (see section 3.2 and chapter 6).

3.2 Standard Frequency range and Maximum Number of Minutes outside the Standard Frequency Range

The Standard Frequency range is defined by GL SO as the *defined symmetrical interval around the nominal frequency within which the system frequency of a synchronous area is supposed to be operated*. The Standard Frequency range is set the same as the *highest permissible variation in the frequency during normal state*[12] in the current Nordic System Operation Agreement, i.e. +/- 100mHz.

Both definitions seem to indicate that in normal circumstances the frequency shall be within the Standard Frequency range. The *frequency quality defining parameter* defined by the GL SO allows the frequency to be outside the Standard Frequency range for 15,000 minutes, which is 2.9% of the time.

[11] The information in these two sentences is not explicitly described in the GL SO, source is Erik Svensson/Svk.
[12] Existing SOA, appendix 3, section 1.1 Quality standards

The Nordic Frequency Containment Process (FCP) is divided in a 'normal' and 'disturbance' process[13]. The intention is that the FCR for normal operation (FCR-N) is used for continuous imbalances and that FCR-D is used for incidental disturbances. The activation of the two is linked to the definition of the Standard Frequency range, i.e. if the frequency is inside the +/- 100mHz range, FCR-N is activated and if the frequency is outside the +/- 100mHz range disturbance reserves respond. This assumes that a frequency outside the +/- 100mHz range indicates that there is a disturbance. However, only a very small share (less than 10%) of the time outside the +/- 100mHz range is currently caused by disturbances. Consequently, FCR-D is mostly used for mitigating 'normal' imbalances.

Considered in a historical perspective, the Standard Frequency Range, MoNB, FCR-N and FCR-D were designed to correctly respond to the specific needs of the system in 'normal' situation (most of the time) and disturbances (1-2 times per week), i.e. a slow 'balancing' for normal situations and a fast response for disturbance situations. Considering the frequency statistics from the previous century this seems to reflect the situation at that time. Since 2000, the number of minutes outside the normal band increased gradually especially with 'normal' situations. Consequently, FCR-D responds mainly to normal situations now. The main consequence of this is that the amount[14] of FCR-D that is left for a real disturbance is not sufficient anymore. Chapter 5 will show that this effect has a major contribution to the risk of UFLS.

The choice for a Standard Frequency range of ±100mHz and the allowed number of excursions from this range shall be considered in combination with the range in which FCR-N and FCR-D are active. Since over 90% of the minutes outside this range is not related to disturbances, there seems to be a mismatch between the situation and the applied reserves. This mismatch could be corrected by changing the *frequency quality defining parameter* (allowed number of minutes outside the Standard Frequency Range) or detaching the frequency range in which FCR-D is active from the Standard Frequency Range[15].

3.3 Maximum instantaneous frequency deviation

The *maximum instantaneous frequency deviation* is currently defined as ± 1000mHz and therefore allows an instantaneous frequency of down to 49.0Hz. This leaves 200mHz to the first trigger frequency of the automatic UFLS relays at 48.8Hz. This 200mHz buffer seems reasonable, and includes a margin for geographic variations in frequency and inaccuracies in models and measurements[16]. Figure 3 shows an example of the geographic variations in frequency.

[13] There are differences in how FCR respond in the Nordic countries, mostly due to differences in technology used in the power plants (hydro, thermal).
[14] This is valid for the obligation of reserves as specified in the 2016 Nordic System Operation Agreement.
[15] This would imply change of characteristics for FCR-D (activation range, volume or speed).
[16] A UCPTE document from 1997 (see annex E) splits the 200mHz margin used in Continental Europe into four parts: 1) Possible stationary frequency deviation before the disturbance (50mHz), 2) insensitivities of the turbine governor (20mHz); 3) larger dynamic frequency deviation at the geographic location of the disturbance which is not taken into account by the simulation model (50mHz); and 4) other simulation model inaccuracies, approx. 10% (80mHz).

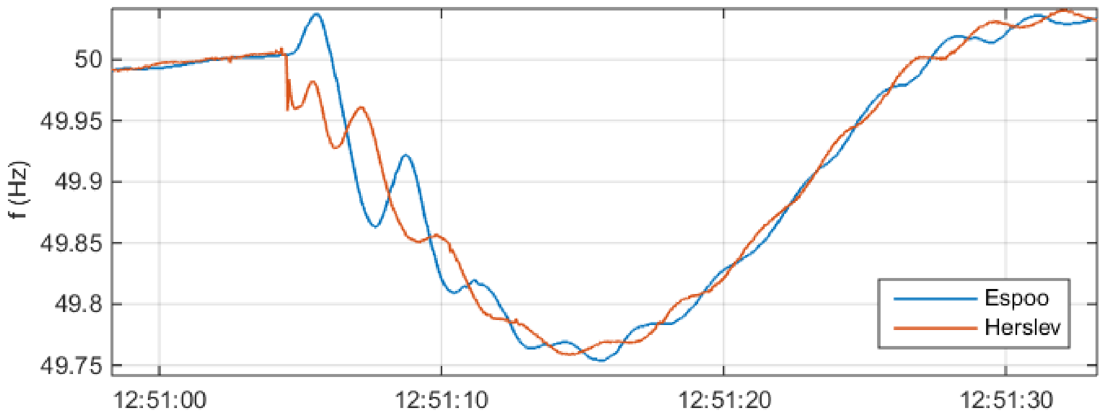

Figure 3: Frequency in Espoo (Southern Finland) and Herslev (Denmark) after a loss of 580MW

The Continental European synchronous area also applies 200mHz as a margin, but includes a 50mHz margin for the frequency deviation before the disturbance. The Nordic synchronous area does not need this margin since it is assumed that the disturbance starts at 49.9Hz.

Although both load and generation should be capable of withstanding instantaneous frequencies between 49.0 and 51.0Hz, there is very little experience in the frequency areas close to 49.0 and 51.0Hz. Consequently, it is not sure if certain load or generation will stay connected if the frequency approaches these limits. If they trip, it may make the situation worse. Since calculations show that in some situations[17] a dimensioning fault could result in a frequency of close to 49.0Hz, additional measures (e.g. more or faster FCR) should be implemented to keep the frequency inside the 49.0-51.0Hz range[18].

3.4 Maximum steady-state frequency deviation

The GL SO defines *steady state frequency deviation*[19] as the 'absolute value of frequency deviation after occurrence of an imbalance, once the system frequency has been stabilised'. Since the Frequency Containment Process (FCP) has the objective to stabilise the frequency[20], the steady state is implicitly defined as the situation after a disturbance in which the FCP has been completed and the Frequency Restoration Process (FRP) has to start. It shall be noted though that with the relatively slow FCR-N activation (120-180s) and the relatively fast aFRR and mFRR activation in the Nordics, these periods may overlap, and that other imbalances may further impact the frequency. It is emphasized that the FCR response differs between the Nordic countries.

In a simulation environment, the *steady state frequency deviation* could be easily determined. However, the examples in Figure 4 show that in practice it will not always be unambiguous to recognise the steady state.

[17] Especially with low frequency before the disturbance, low inertia levels, limited amount of emergency power of HVDC lines, limited self-regulation of load and limited amount of FCR-D (see chapter 4).
[18] the work with more/faster FCR is a part of a parallel project studying measures to handle n-1 situations for low system inertia situations.
[19] GL SO, article 3(157)
[20] GL SO, article 142

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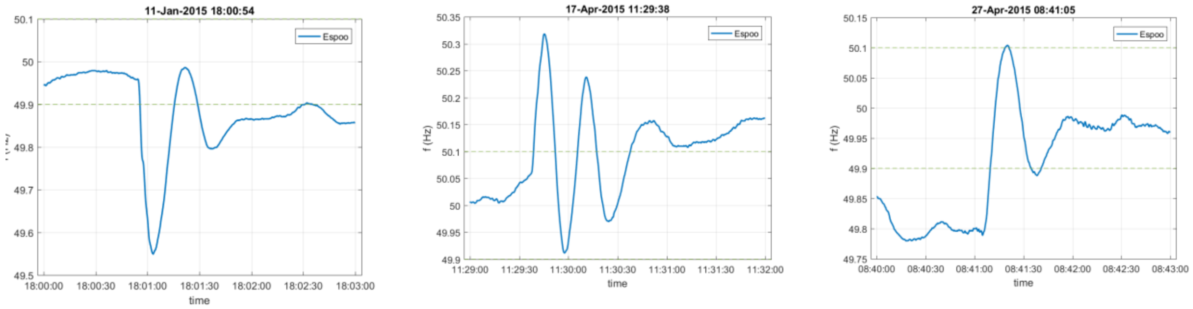


Figure 4: Three frequency responses after large disturbances in 2015 (source: Fingrid's f-report 2015)

FQ2 proposes the average frequency covering 90-150s after the disturbance as proxy for the *steady state frequency*[21]. Figure 5 shows some examples.

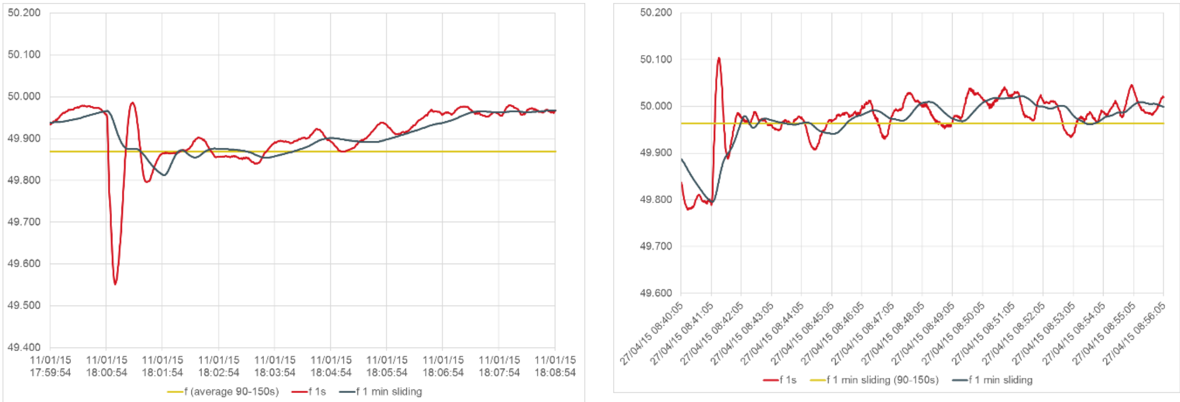


Figure 5: Two frequency responses after large disturbances in 2015 (red line), with 'rolling average of the previous 60s period' (dark blue line) and the proposed proxy for steady state (yellow line)

For the Nordic system, the *maximum steady-state frequency deviation* does not have a direct link to the UFLS risk. Hence, the *maximum steady-state frequency deviation* implicitly indicates the frequency range at which FCR shall be activated. The *Maximum steady-state frequency deviation* therefore directly links to the definition of FCR-D, which requires an increasing activation from 0% to 100% if the frequency reduces from 49.9 to 49.5Hz. *As long as the FCR-D characteristics are defined like this, it is logical to keep the maximum steady-state frequency deviation to ±500mHz.*

[21] This proxy takes into account that 1) FCR-N and FCR-D activation shall be stabilised, i.e. the measurement shall not be too early; 2) FRR activation shall not have been started, i.e. the measurement shall not be too late; 3) Other imbalances will have the lowest possible influence, i.e. the measurement shall not be too late; (60s) Oscillation in the frequency shall be filtered out.

4 Parameters that affect Under Frequency Load Shedding (UFLS) Risk

As discussed in chapter 2, the high level objective of *maintaining frequency quality* is to limit the risk of UFLS. Section 4.1 to 4.6 describe the parameters that affect the probability of Under Frequency Load Shedding (UFLS) after a disturbance.

The descriptions include illustrations that show the effect of changing the parameters to the frequency nadir. The illustrations show the effects for two ‘base-case’ studies, one for a minimum inertia situation and one for a maximum inertia situation. For both base cases, a ‘worst’ case alternatives have been added that reflect variations on inputs and assumption. The same cases have been applied in section 4.1 to 4.6 which makes them comparable. Table 1 describes these situations.

Table 1: Parameters used for ‘base-case’ and ‘worst-case’ studies presented in this chapter.

	Base Case situations		Worst Cases situations	
Parameter	**Minimum inertia case summer 2015**	**Maximum inertia case winter 2015/16**	**Minimum inertia case summer 2015**	**Maximum inertia case winter 2015/16**
Date/time	3 June 2015, 4-5h	21 Jan 2016 8-9h	3 June 2015, 4-5h	21 Jan 2016 8-9h
Inertia	121GWs	286GWs	*-/-25%: 91GWs*	*-/-25%: 215GWs*
Dimensioning fault	1250MW	1450MW	1250MW	1450MW
FCR-D volume	1528MW	1498MW	*Dimensioning fault -/- 200MW: 1050MW*	*Dimensioning fault -/- 200MW: 1250MW*
Emergency Power by HVDC links (EPC)	751MW	647MW	*0MW*	*0MW*
Self-regulation of load to frequency	1%/Hz	1%/Hz	*0.5%/Hz*	*0.5%/Hz*
Self-regulation of load to Voltage	No voltage dependency of load			
FCR-D characteristics	The project is using the RaR model, including FCR models developed in the RaR project in 2011[22].			

[22] requirements for automatic Reserves in the Nordic Synchronous system - Simulink Model description (final), 2011-07-29.

4.1 Inertia

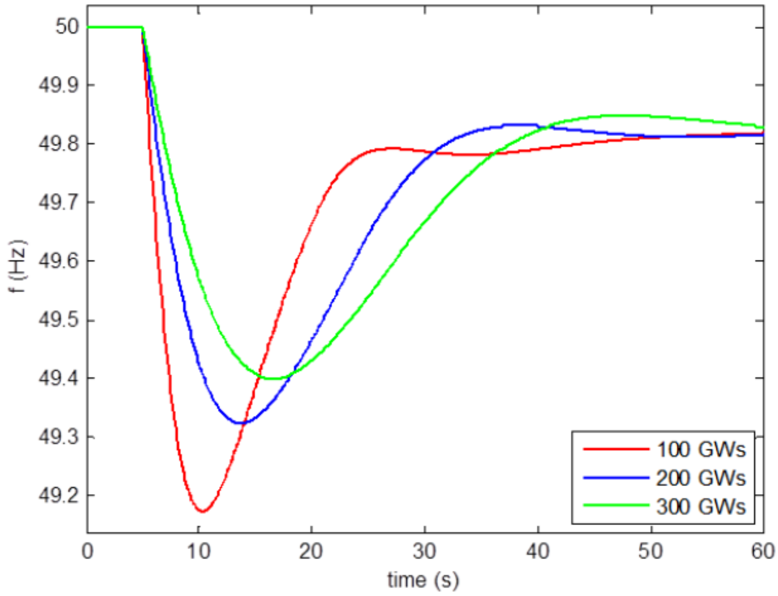


Figure 6: Simulated response for frequency response when losing a large generating unit, as a function of different system inertia levels. (source: figure 23 of report NAG - Frequency Quality Report, Version 2.0 April 2015)

Inertia (or kinetic energy in the system) depends on the characteristics and the capacity of the synchronously rotating machines (generation and motors) connected to the network. The inertia of the system determines the Rate of Change of Frequency (RoCoF) directly after an incident. For a lower inertia level, the frequency will reduce faster. Consequently, the reserves will only be able to balance the imbalance at a lower frequency which results in a lower frequency nadir. Figure 6 shows an example for three levels of inertia.

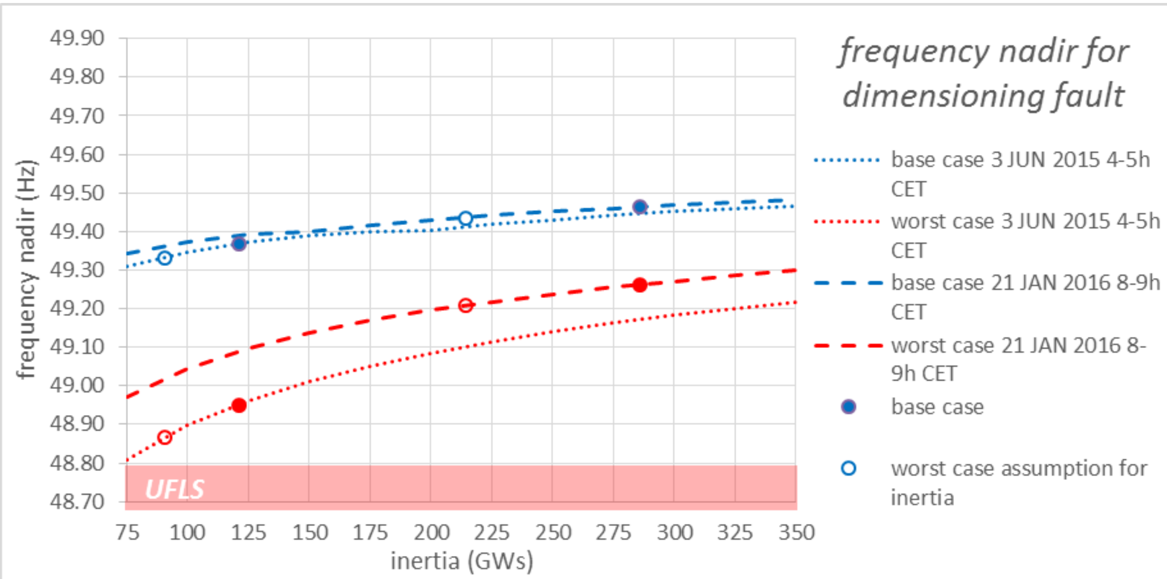


Figure 7: Impact of inertia on the frequency nadir for minimum inertia case (3 June 2015, 4-5h) and maximum inertia case (21 January 2016, 8-9h), both base case and worst case.

Figure 7 shows that the Inertia affects the frequency nadir for a range of inertia levels. For the current range of inertia levels (in 2015: 121-286GWs), the impact on the frequency nadir is limited to approx. 0.1Hz in the base case, but can increase to more than 0.3Hz if the worst case assumptions are applied.

The inertia 1 project prepared a model that is being used to estimate the inertia based on the generation dispatch in the four Nordic countries. The accuracy of this estimation is reasonable for real-time and historical situations. The inertia 2 project estimated inertia of 2020 and 2025, by using market simulations for 33 hydro years. *The impact can be estimated with a reasonable accuracy.*

FQ2 concludes that the impact of inertia is significant, but that it can be estimated with reasonable accuracy[23]*. We further conclude that the impact of inertia will increase in the 'worst case' situations, i.e. if the other relevant parameters are closer to their limits.*

4.2 Self Regulation of load

Previous work stated that *"Different load types in the system behave differently regarding power consumption during a situation where voltage and/or frequency deviates from their nominal values. This is called "self regulating" of load."*[24]. In this FQ2 project, we focus on the frequency dependency of load only[25] and refer to it as self regulation of load.

Self regulation of load means in practice that an imbalance is partly mitigated by the response to load. E.g. if a 1000MW imbalance causes a frequency drop of 1Hz at the time that the consumption in the Nordic system is 50,000MW, 250MW of the imbalance is mitigated by self-regulation if the self-regulation is 0.5 %/Hz.

Unfortunately, there is little knowledge about the amount of self-regulation in the Nordic system. The last study from 1995[26] gives a figure *0.7 % / 0.5Hz for a low load situation.* The assumption that is currently applied by the Nordic TSOs for the determination of the amount of FCR-D is that self regulation accounts for 200MW[27]. Implicitly it is assumed that it acts instantaneously.

Currently, a large Nordic investigation on load modelling is being performed by STRI in cooperation with the TSOs. The project started in 2015 and is expected to provide results by the end of 2018. Phase 1 of this project developed the methodology. In phase 2 the methodology is being tested in chosen locations of the grid. Phase 3 in 2017-2018 will consist of applying the developed methods on large scale in order to find the load modelling parameters to be used in various simulations.

Figure 8 shows the impact of self regulation on the frequency nadir. The figure shows that for the base case, the influence of reducing the self regulation from 1.0%/Hz to 0%/Hz is approximately 0.1Hz. For the worst case the difference may be more than 0.4Hz. The figure also shows that especially in the 'worst minimum inertia case' a lower self regulation could easily result in UFLS.

[23] For future, this can be done using market studies. This is done in the 'Future System Inertia 2' project
[24] Section 8.7 of 'NAG – Frequency Quality Report, version 2, April 2015
[25] The FQ1 report suggests that the voltage dependency needs to be taken into account. The voltage dependency may be influenced by the geographical location of the disturbance and requires load flow studies. Since the FQ2 project's focus is on frequency, the influence of voltage dependency has been neglected in this report. Note though that this adds inaccuracy to the results that needs to be taken into account in our results.
[26] Gunilla le Dous and Anna Holmer, Lastens frekvensberoende I det nordiska kraftsystemet, Chalmers Examensarbete No. 95/96:0
[27] System Operations Agreement, Appendix 2, Section 4.1.2 (version 2016-06-23)

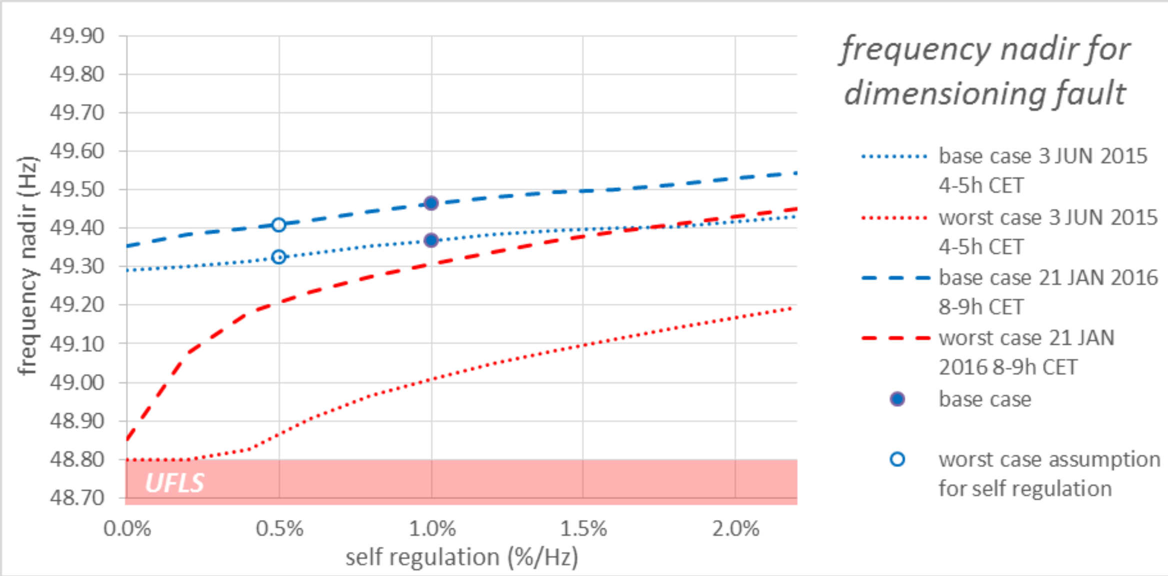


Figure 8: Impact of self regulation of load (frequency related) on the frequency nadir for minimum inertia case (3 June 2015, 4-5h) and maximum inertia case (21 January 2016, 8-9h), both base case and worst case.

It shall be noted that the 1%/Hz assumption is largely uncertain and Figure 8 shows self-regulation may have a big impact on the frequency nadir and consequently the UFLS risk. This report therefore applies 0.5%/Hz for self regulation in our worst case scenario. Once the STRI study has been finalised, this assumption can be updated.

4.3 Frequency controlled Emergency Power by HVDC links, boilers or other directly disconnectable load

(this section is drafted for Emergency Power by HVDC links, but the same principles apply to loads that can be automatically and directly be disconnected by frequency relays. This includes the agreed automatic load shedding as referred to in the existing Nordic System Operation Agreement[28], e.g. industrial, district heating and electric boiler consumption)

Frequency controlled Emergency Power (EPC) is the power regulation on HVDC links activated by automatic systems in case of a frequency deviation larger than the setting for this HVDC link. EPC is only delivered if available. I.e. if the entire capacity of the HVDC link is used for importing power to the Nordic system, there will be no capacity available anymore on this HVDC link to provide EPC[29]. EPC acts very fast (almost instantaneously) and has therefore an immediate effect on the imbalance in the system. The *maximum* EPC amount (1100MW[30]) is in the same order of magnitude as the currently contracted FCR-D (approx. 1200MW) and the reference incident (approx. 1450MW). EPC power will stay available until a dispatcher manually changes the transfer over the HVDC link to the transfer of before the disturbance. This is different for the contribution of FCR-D and self regulation which is reduced automatically if the frequency recovers.

Although available figures for available EPC were not completely accurate, indications exist that for more than 80% of time at least 300MW of EPC is available.

Figure 9 shows the impact on the frequency nadir. The figure shows that EPC contributes significantly to the frequency quality by approx. 0.1Hz in the maximum inertia case and approx. 0.3Hz in the minimum inertia

[28] System Operations Agreement, Appendix 2, Section 4.1.2 (version 2016-06-23)
[29] An exception of this is the Kontek link, which is using the ‘overload capacity’ of 10% for providing at least 50MW, even if the link is loaded to its rated capacity of 600MW
[30] System Operations Agreement, Appendix 5, Section 2.1, Figure 2 (version 2016-06-23)

case. For both ‘worst case’ scenarios, the influence is even larger: approx. 0.2Hz in the maximum inertia case and approx. 0.4Hz in the minimum inertia case.

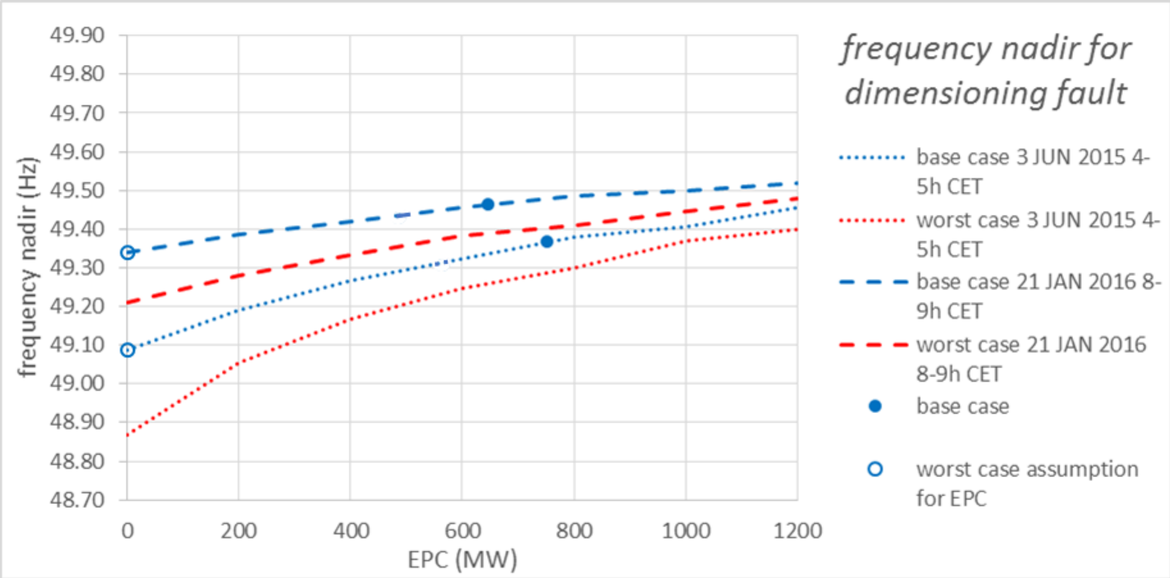


Figure 9: Impact of Emergency Power on the frequency nadir for minimum inertia case (3 June 2015, 4-5h) and maximum inertia case (21 January 2016, 8-9h), both base case and worst case.

We conclude that EPC has a major impact on the frequency nadir and that there is a lot of potential. Although Fingrid prepared a very useful report on the availability of EPC, this report was based on many assumptions and there is still a lot of uncertainty to be assessed.

4.4 Frequency before incident

A lower *frequency* before the disturbance means that more FCR has already been activated. Consequently, less FCR will be available for mitigating the imbalance caused by the disturbance which may increase the probability of load shedding. The left hand diagram of Figure 10 shows the histogram for frequency in 2015 and the right hand figure zoom in on the times that frequency is below 49.90Hz. In 2015, the excursions below 49.90Hz are pretty much randomly distributed over the year[31]. Furthermore, 11.7 minutes (0.0022% of time) the frequency was below 49.80Hz.

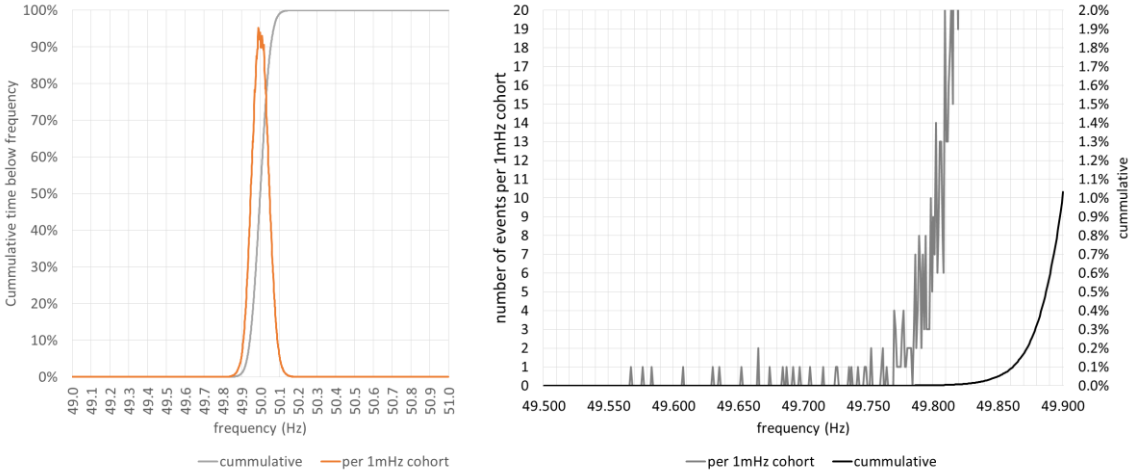


Figure 10: Histogram of frequency in the Nordic system in 2015 (Source: Svk 5 second data)

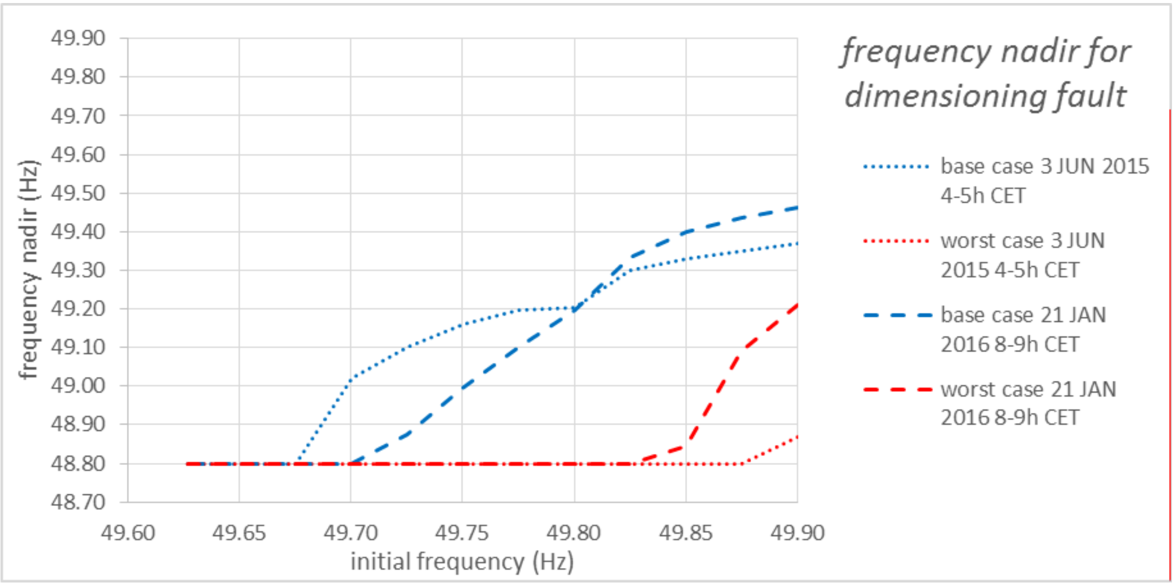


Figure 11: Impact of initial frequency (frequency before the incident) on the frequency nadir for minimum inertia case (3 June 2015, 4-5h) and maximum inertia case (21 January 2016, 8-9h), both base case and worst case.

[31] This may be influenced by the use of aFRR in morning ramp and sunset hours in 2015. During the morning ramp hours in the first half of 2016, the amount of time outside the 49.9-50.1Hz range was typically larger than in other hours. aFRR was not contracted in the first half of 2016.

Figure 11 shows the impact of the frequency before the incident (initial frequency f_0) on the frequency nadir. The figure shows that for the worst case situation, especially in the minimum inertia case, an initial frequency that is very little below 49.90Hz may result in a frequency of less than 48.8Hzwill trigger UFLS.

Between 49.90Hz and 49.80Hz, the impact on the frequency nadir is around 0.2Hz for the base cases and more than 0.5Hz on the worst case for the maximum situation. It shall be noted that this impact is far larger than the reduction of the initial frequency of 0.1Hz. The reason for this is that part of the FCR-D has already been activated.

4.5 Size of the disturbance

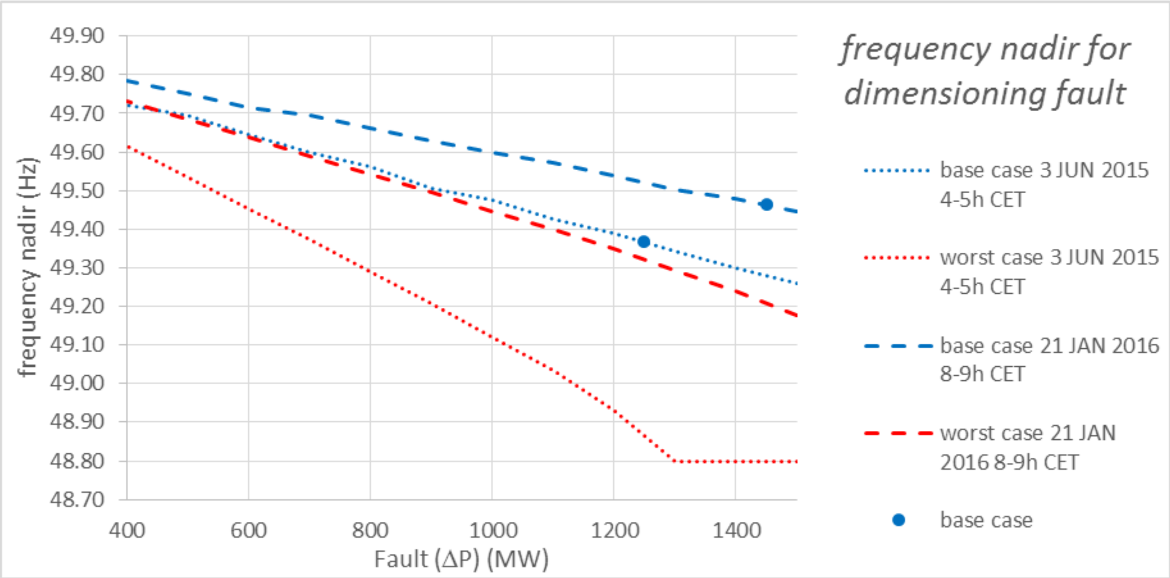


Figure 12: Impact of the size of the fault (ΔP) on the frequency nadir for minimum inertia case (3 June 2015, 4-5h) and maximum inertia case (21 January 2016, 8-9h), both base case and worst case.

Figure 12 shows the impact of the size of the disturbance (ΔP) on the frequency nadir. The figure shows that for the maximum inertia case, the frequency nadir will decrease with 0.03Hz per 100MW increase of ΔP. For the minimum inertia case this is approx. 0.04Hz. For the worst case situations, these values are larger and not linear anymore, with the highest values for the largest faults.

Figure 12 shows that even in the worst case situation, it is unlikely that disturbances below 1000MW will trigger UFLS.

4.6 FCR-D amount and settings

FCR-D is the fast active reserves that *"shall be activated at 49.9Hz and shall be fully activated at 49.5Hz. It shall increase virtually linearly within a frequency range of 49.9-49.5Hz."*[32]. The effectiveness of FCR-D largely depends on the speed of the FCR-D response in relation to the RoCof (see section 4.1). This issue is being studied by the FCP project and new requirements for FCR-D are being developed. In addition to speed, FCR-D effectiveness depends on the amount that is available at the time of the incident. This depends on both the capacity of FCR-D available in the system and the amount that already has been activated because the frequency before the incident was already below 49.9Hz.

Measurements that have been performed in the FCP project revealed that in practice, we unfortunately have little information about the governor settings of the hydro units and the response of the hydro units to these

[32] System Operations Agreement, Appendix 2, Section 4.1.2 (version 2016-06-23)

settings. However, because of the measurement program of the FCP project, more information is available than during the construction of the RaR model in 2011.

The amount of FCR-D in the Nordic system includes both the contracted FCR-D amount and the additionally provided FCR-D which is not contracted. The FCR-D that is not contracted may exist due to a number of reasons:

- Fixed governor settings in hydro units that are not changed if FCR-D is not contracted;
- Governors delivering up to their rated power, which may be more than the contracted capacity.

The additional FCR-D is assumed to be a mainly present in Norway and it is assumed that this will be reduced. For example, Statnett reports for the minimum inertia case 799MW of FCR-D (instead of estimated required 321MW) and for the maximum inertia case 611MW of FCR-D (instead of estimated required 363MW).

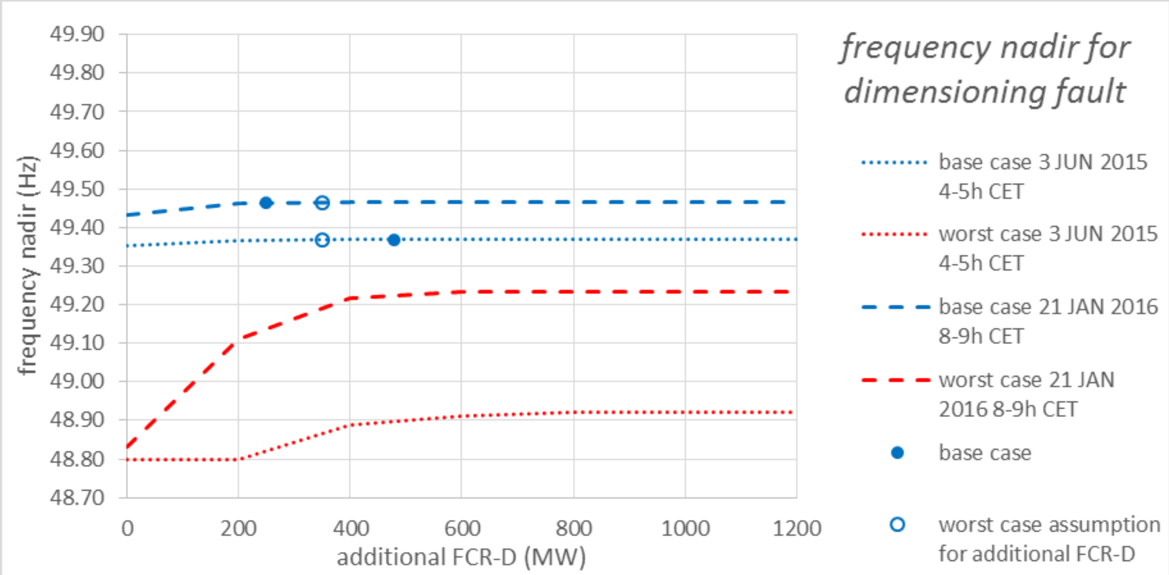


Figure 13: Impact of additional FCR-D volume on the frequency nadir for minimum inertia case (3 June 2015, 4-5h) and maximum inertia case (21 January 2016, 8-9h), both base case and worst case.

Figure 13 shows for the frequency nadir as function of additional FCR-D in Norway. The figure shows that the impact of additional FCR-D is limited for the base cases. However, for the worst cases, additional FCR-D may make the difference between load-shedding or not. This result is partly due to the way of modelling the additional FCR-D in Norway, which is done at the same rate of MW/Hz. Consequently, the response is only increased at the lower frequency levels.

4.7 Summary and Conclusion

The conclusion of the analysis that has been presented in this chapter is that the individual impacts of FCR-D, inertia, self-regulation of load, EPC and initial frequency are all significant and comparable in size. Furthermore, the combined effect of the 'worst case' assumptions on the frequency nadir is even larger than the sum of the individual impacts. Consequently, all these parameters need to be taken into account when studying the UFLS risk.

5 Probabilistic methodology for determination of UFLS risk

Based on earlier work by Svk, the Frequency Quality 2 project established a probabilistic methodology for estimating the risk for automatic Under Frequency Load Shedding (UFLS risk)[33]. Furthermore, the FQ2 project worked on the application of the results, including finding the socio-economic optimum. This chapter 5 describes the background, assumptions, results and sensitivities for estimating the UFLS risk. Chapter 6 discussed the applications of the model, including the socio-economic optimum. Annex A provides a full description on the model itself.

5.1 Probabilistic Methodology

5.1.1 Estimating UFLS risk for one system situation

The probabilistic methodology starts with estimating the UFLS risk for a system situation at a certain time period *T*, e.g. an hour or a minute. This system situation is characterised by the consumption and production in the system, the amount of FCR-D, the available Emergency Power (EPC) and the inertia level. Furthermore, there are assumptions on the self-regulation of load and models for FCR-D characteristics in different countries.

For this system situation, UFLS is triggered if the combination of frequency before the incident f_0 and the disturbance size ΔP results in a frequency nadir f_{nadir} that triggers UFLS. Using a number of simulations for different combinations of f_0 and ΔP, a function for f_{0_lim} can be constructed that indicates if UFLS is triggered for a given ΔP if f_0 is below f_{0_lim}[34]:

$$f_{0\_lim} = \alpha \Delta P + \beta \qquad (1)$$

Figure 14 shows an example.

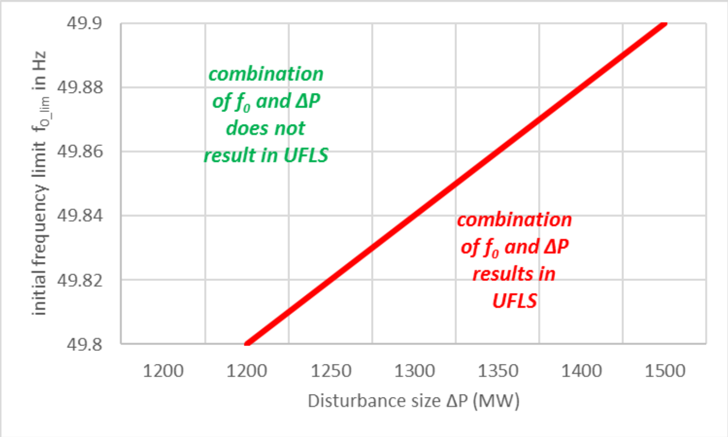


Figure 14: Example of f_{0_lim} equation (1).

Based on (1), the probability that UFLS is triggered by disturbance *i* is calculated by multiplying the probabilities that the frequency is below $f_{0\_lim\_i}$ and the probability of disturbance *i:*

$$P(UFLS_i) = P\left(f_0 < f_{0\_\lim\_i}\right) \cdot P(disturbance_i) \qquad (2)$$

The total probability for load shedding for this time period *T* is defined as the sum of the probabilities for all *n* disturbances on the disturbance list:

$$P(UFLS_T) \ = \ \sum_i^n P(UFLS_i) \qquad (3)$$

In this report UFLS risk is expressed in number of UFLS events per year, i.e.

[33] Note that this is in fact the UFLS *probability* since *risk* would also include the impact.
[34] The current model applies a linear function. It shall be noted though that the relationship is not linear. An improvement to the model could be to more accurately model the relationship.

$$UFLS\ Risk = \frac{1}{P(UFLS_T)} \quad (4)$$

5.1.2 UFLS risk for an entire year

The probabilistic model could estimate UFLS risk for an entire year by repeating the UFLS estimations discussed in section 5.1.1 above for all hours T individually, taking into account inertia, consumption, FCR-D amount of each hour. However, since this would result in a lot of additional simulations, the calculation time would be unacceptably long. For this reason, a correlation between consumption, production and consumption has been assumed[35].

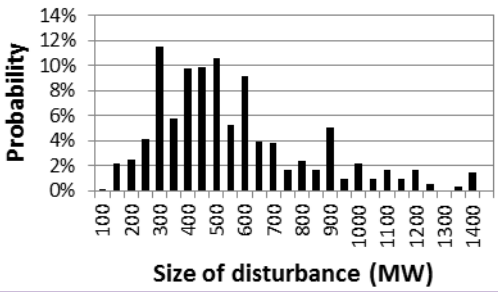
5.2 Assumptions and Input parameters

Table 2 provides a summary of the assumptions that have been used.

Table 2: Assumptions and input parameters for UFLS risk estimations

Parameter	Base case assumption	Comment
FCR-D characteristics	The project is using the RaR model, including FCR models developed in the RaR project in 2011[36].	The RaR model could be updated with the results of the measurement program of the FCP project and/or the future requirements for FCR being developed by the FCP project.
FCR-D volume	For the simulations for 2015 and 2016, two scenarios: 1. 1450MW for all hours; 2. for Norway historical values[37], for other countries required values For forecasts for 2020 and 2025, FCR-D volume is assumed to be equal to 1450MW	
Frequency	Historical values are used for simulations of 2015 and 2016 with existing f quality. For studies with different numbers of minutes outside the standard frequency range, a standardised distribution of minutes over the frequency below 49.95Hz that is based on historical distributions for recent years with 5,000 to 15,000 MoNB (see annex A)	The Number of Minutes Outside the normal band for the April 2015 to March 2016 period was 8146, of which 3614 minutes were below 49.9Hz. For extrapolation to 500, 20,000 and 25,000 MoNB the same distribution is assumed. However, since there is no experience with these levels, it is not possible to verify this assumption
Inertia	Historical values are used for 2015 and 2016[38] Forecasts for 2020 and 2025[39]	

[35] Data for April 2015 to March 2016 showed that consumption and inertia were highly correlated.
[36] requirements for automatic Reserves in the Nordic Synchronous system - Simulink Model description (final), 2011-07-29.
[37] Estimates from Statnett
[38] Estimates from the real time inertia estimation tool that was developed in the inertia 1 project
[39] Estimates from inertia project forecasts are based on 33 hydro years (1980-2012).

Parameter	Base case assumption	Comment
Self-regulation of load to frequency	Factor of 0.5%/Hz	*This is a very rough estimate* The latest study on this parameter was done in 1997[40] and concluded that self-regulation of load was 0.7% of load for 0.5Hz. A project[41] is ongoing that studies the self-regulation of load and expects results by 2018
Self-regulation of load to Voltage	No voltage dependency of load	FQ1 report concludes that the influence of voltage on load may be larger during a disturbance than the influence of frequency. This largely depends on the location of the fault.
Emergency Power by HVDC links (EPC)	0MW	The influence of EPC is studied by sensitivity analysis (see section 5.3.3).
Load	Correlation assumed with inertia. Linear function between consumption and inertia determined based on consumption data: For history: taken from Nordpoolspot Forecasts for 2020 and 2025 by the Inertia 2 project[42]	The reason for using a correlation function is that the number of simulations can be drastically reduced to one different load scenario per inertia level and not the entire range. Analysis shows that correlation between inertia and consumption is good (R^2=0.87 for 2015 data).
Types of disturbances	Only (n-1) disturbances	The influence of common cause faults is studied by sensitivity analysis (see section 5.3.3). The probability that two independent faults happen at the same time is neglected[43].
Disturbance sizes and probabilities	Based on registered disturbances between 2004 and 2015[44], the model is using the size distribution of these historical disturbances and a frequency of 100 disturbances per year. Improvement of this assumption is possible. FQ2 group recommends structurally collecting faults.	
Trigger level of UFLS	UFLS is assumed to trip at 49.0Hz. This assumption is based on the 'maximum instantaneous frequency deviation' of 1000mHz (from 50Hz) set in the GL SO.	This assumption leaves 200mHz to the first trigger frequency of the automatic UFLS relays at 48.8Hz (see section 3.3)

[40] Gunilla le Dous and Anna Holmer, Lastens frekvensberoende I det nordiska kraftsystemet, Chalmers Examensarbete No. 95/96:0.
[41] Ongoing project with the Nordic TSOs and Stri.
[42] The forecasts are based on 33 hydro years (1980-2012).
[43] It shall be noted that the model could be easily take into account other types of disturbances, including n-x (x>1) and common cause failures.
[44] File 'f(t) vs. fault size.xlsx'

5.3 Simulation Results

5.3.1 Historical analysis

Table 3: Results of simulations for the period from April 2015 to March 2016, using the assumptions in Table 2. Note that the disclaimer in section 1.5 is applicable.

	Average FCR-D	UFLS risk (years between UFLS events)
Required FCR-D	1450MW	23 years
Historic FCR-D	1450MW + actual additional FCR-D[45] (on average 339MW)	38 years

Historical simulations with the probabilistic model have been performed for the period from April 2015 to March 2016. Table 3 shows the results for the situation with the required FCR-D amounts and with historic FCR-D amounts, including additional delivery from Norway on top of the required Norwegian share. The table shows that additional FCR-D from Norway had significant impact on the UFLS risk.

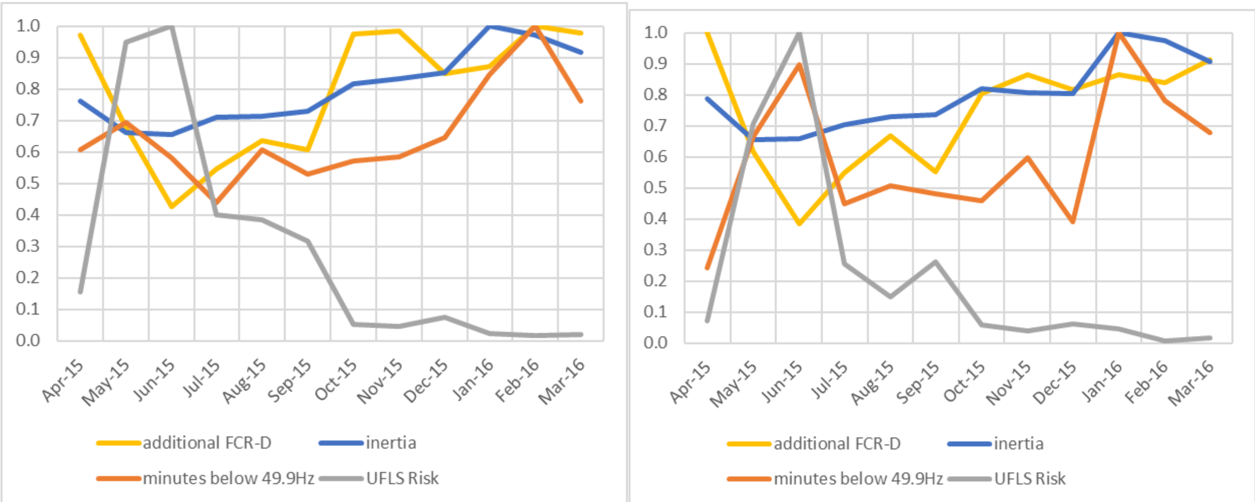


Figure 15: For the historical situation (with historic FCR-D): Normalised Monthly Average Inertia, Minutes below 49.9Hz and UFLS risk compared for all hours (left) and the 'ramping hours from 5:00-8:00 on working days (right) as share of the maximum value.

Figure 15 compares per month the average inertia, the average minutes below 49.90Hz and the resulting UFLS risk for the historical situation without taking the additional delivery of Norwegian FCR into account. The right hand graph provides the same picture, but for the ramping hours during working days only. The figures show that especially in summer, the UFLS risk is high.

[45] Close to normally distributed with standard deviation of 191MW. During 95% of time, the additional FCR-D is at least 250MW.

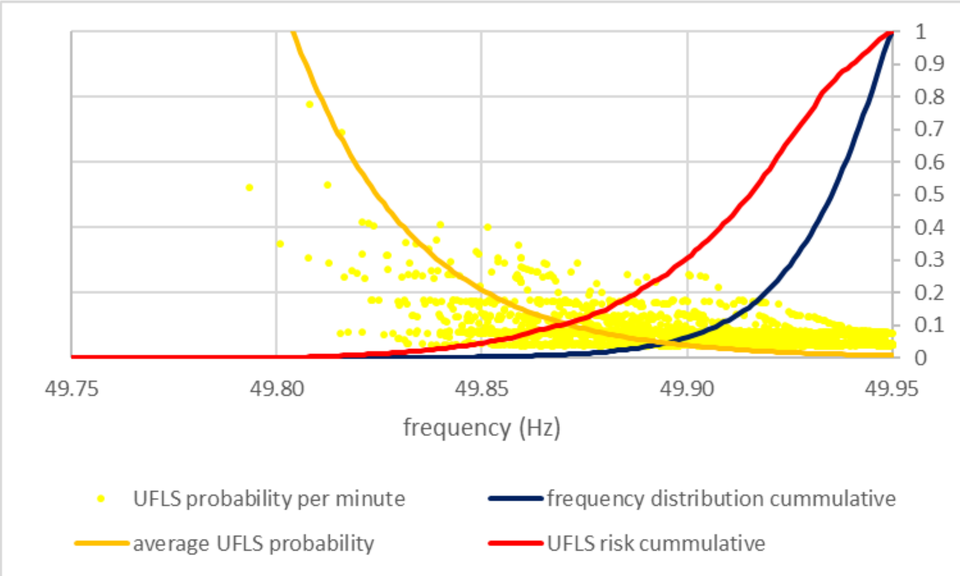


Figure 16: For the historical situation (with historic FCR-D): Normalised UFLS probability per minute, average UFLS probability per frequency level, cumulative UFLS risk and cumulative frequency distribution – as function of frequency. Note that the disclaimer in section 1.5 is applicable.

The yellow dots in Figure 16 indicate the UFLS probability for a certain minute in the study period. The orange line shows the average UFLS probability for each frequency level. The figure shows that the UFLS risk increases rapidly if the frequency decreases from 49.95 to 49.80Hz. At the same time, the blue line indicates that more than 99% of the time that frequency is below 49.95Hz, the frequency is in between 49.85-49.95Hz. The red line indicates that the minutes within this frequency range cause at least 90% of the total UFLS risk[46]. The main reason for UFLS risk at high frequencies is that the response of the implemented FCR-D is too slow to cope with the lower inertia situations. In addition to this, between 49.85-49.90Hz normal imbalances are often mitigated by a misuse of disturbance reserves. Consequently, insufficient reserves may be left for preventing UFLS.

[46] It shall be noted that the UFLS risk for cases in which the initial frequency is above 49.95Hz have been ignored in this study. Studying these requires an update of the model.

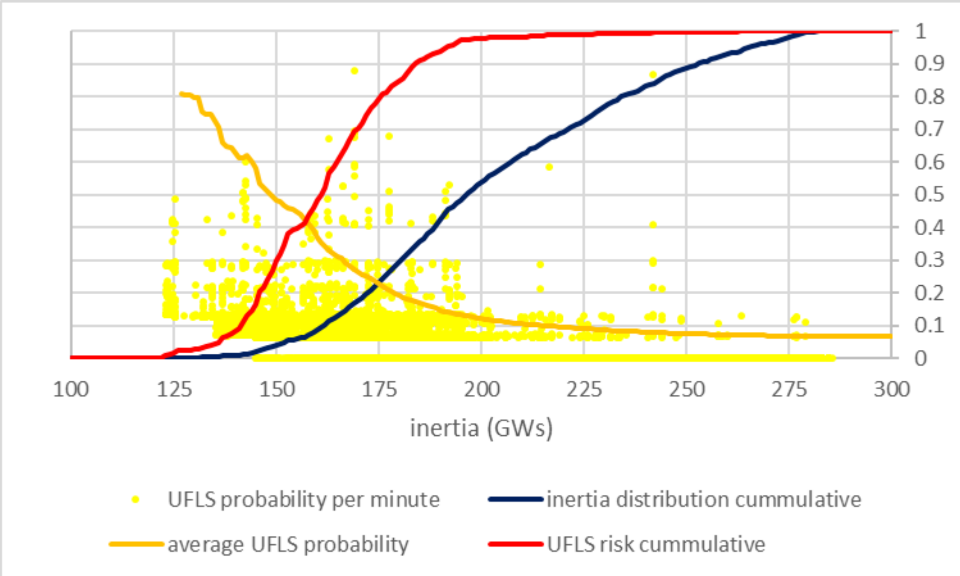


Figure 17: For the historical situation: Normalised UFLS probability per minute, average UFLS probability per inertia level, cumulative UFLS risk and cumulative frequency distribution – as function of inertia. Note that the disclaimer in section 1.5 is applicable.

The yellow bullets and the orange line in Figure 18 show the probability that a disturbance results in UFLS as a function of inertia. The orange line shows that the UFLS probability decreases sharply between 125GWs and 175GWs. The blue line indicates that inertia was below 175GWs for 25% of time, and the red line shows that 80% of the total UFLS risk is resulting from this 25% of time.

5.3.2 Forecasts for 2020 and 2025

Table 4: Results of UFLS risk estimations for 2020 and 2025, based on forecasted inertia and consumption, 1450MW FCR-D and 10000 MoNB. Note that the disclaimer in section 1.5 is applicable.

	UFLS risk (years between UFLS events)
2020	13 years
2025	17 years

Based on market simulations resulting in forecasts for inertia and consumption[47], the UFLS risk has been estimated for 2020 and 2025. Table 4 shows the results, based on the assumption of 10,000 MoNB and a disturbance probability equal to the historical case. Furthermore, the amount of FCR-D was 1450MW.

It shall be noted that these results cannot be directly compared with the results of the historical analysis in Table 3 since the historical values are based on the specific hydro situation in the year, where the 2020 and 2025 forecasts are based on 33 hydro years.

5.3.3 Sensitivity analyses

The probabilistic model described in section 5.1 has many inputs (see section 5.2). In this section sensitivity analyses are described and applied to these input parameters. All sensitivity analyses have been performed for the historical (April 2015 – March 2016) situation.

47 Input from the ‘Future System Inertia 2’ project, market simulation based on 33 hydro years

Self-regulation of load

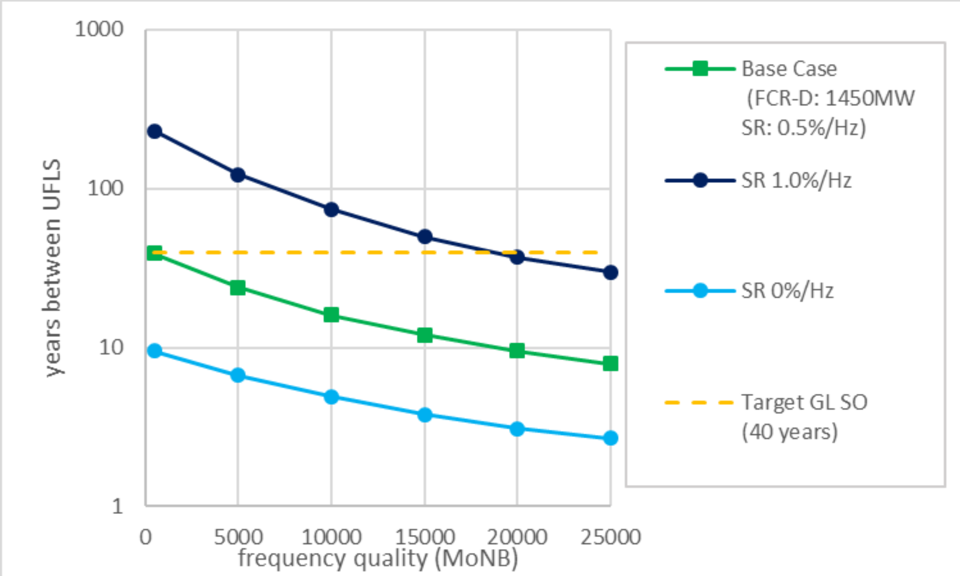


Figure 18: Sensitivity analysis for self-regulation of load Note that the disclaimer in section 1.5 is applicable.

Figure 18 shows the impact of changing the assumption of 0.5%/Hz for self-regulation of load to 0%/Hz and 1%/Hz. The figure shows that the impact of this assumption is significant.

Emergency Power (EPC) by HVDC links / Amount of FCR-D

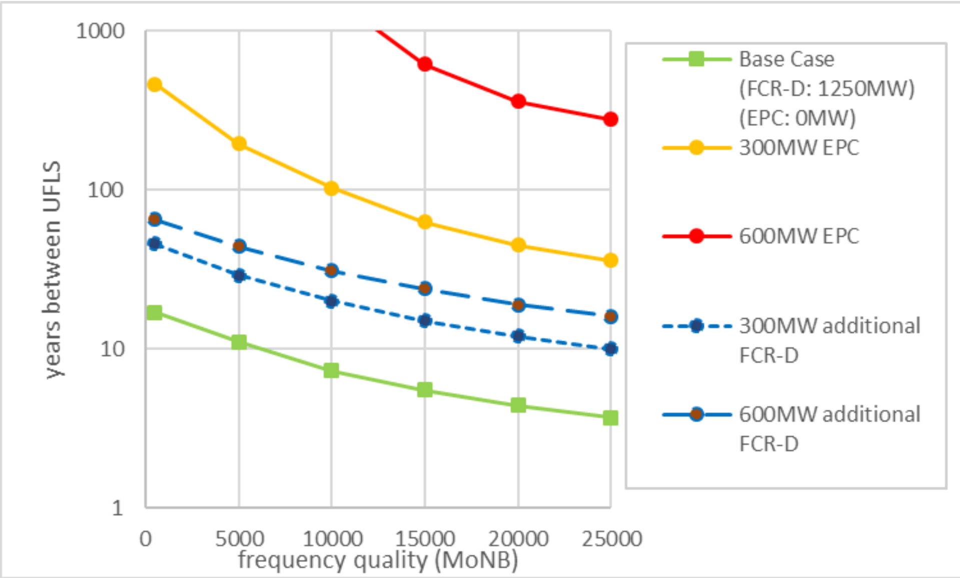


Figure 19: Sensitivity analysis for EPC and FCR-D Note that the disclaimer in section 1.5 is applicable.

The base case does not take into account the contribution of Emergency Power (EPC). Although available figures for available EPC were not completely accurate, indications exist that for more than 80% of the time at least 300MW of EPC is available. Figure 19 shows that the impact of 300MW and 600MW EPC volume is very large[48]. Furthermore, Figure 19 shows that the impact of 600MW of additional FCR-D is far less than the impact of 300MW of EPC.

[48] Note that these volumes have been added for all hours of the year since no hourly figures were available.

FCR-D provided by load may have the same impact as EPC
In the simulations FCR-D is provided by hydro units. If 300MW of FCR-D would be provided by load, it will have the same impact as shown for the 300MW of EPC, i.e. more than the impact of 600MW of FCR-D provided by hydro units. The response time for disconnection of load must be very low, in the order of seconds to have the same impact as EPC.

Disturbances: Adding HVDC link and Common Cause failure

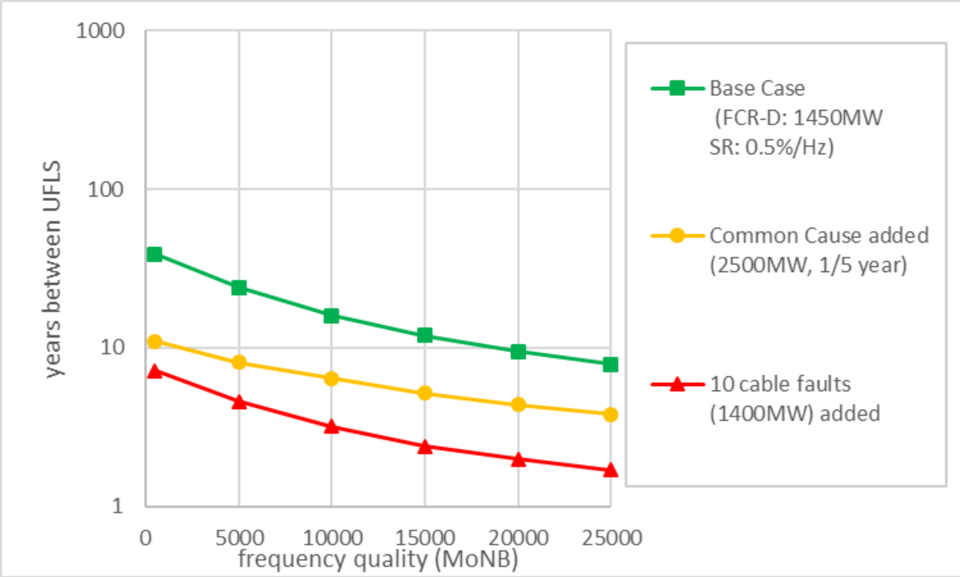


Figure 20: Sensitivity analysis for Common Cause faults and 10 added HVDC cable faults Note that the disclaimer in section 1.5 is applicable.

As explained in section 5.2, the model's disturbance list only includes (n-1) disturbances. The statistics on common cause failures in the Nordics are not sufficient to make a good estimation on common cause sizes and probabilities. The 2004-2015 fault dataset that has been used to populate the disturbance list, included one 'common cause' fault with negative imbalance of 2500MW[49]. The orange line in Figure 20 shows the results of sensitivity analysis with this case assuming that it will take place once in five years: At 10,000 MoNB this fault increases the UFLS risk from 16 to 6.4 years between UFLS.

At this moment and in the next years several new HVDC cables are being be added to the Nordic system. These HVDC links create an additional UFLS risk for two reasons. Firstly, the impact of a trip of a fully loaded HVDC link creates an imbalance that may be (close to) the reference incident. Furthermore, the experience is that especially in the first year of operation, the probability that an HVDC link trips is large[50]. Sensitivity analyses have been performed with 10 additional trips of HVDC links with 1400MW import. The red line in Figure 20 shows a significant increase of UFLS risk, at 10,000 MoNB the UFLS risk increases from 16 to 3.2 years between UFLS[51].

FQ2 concludes that common cause failures may have a significant effect on the estimated UFLS risk, but the influence of changing risks due to e.g. new HVDC links can be even higher. For improving the results for

[49] This was a 2500MW disturbance caused by a large incident at Porjus on 1 December 2005, 15:02h. The resulting frequency nadir was 49.234Hz
[50] Figures for 2016 (document NOG HVDC Trips 2016.pptx) show 53 trips on 10 HVDC links, of which most on the relatively new HVDC links, e.g. 17 on Nord Balt.
[51] The influence of the additional HVDC links on the inertia has not been taken into account in this sensitivity analysis. Consequently, at times of import over the HVDC links, production and therefore inertia in the Nordic system are likely lower than modelled which means that the UFLS risk for these hours is underestimated.

future scenarios, it may therefore be useful to improve the forecasts of the disturbances, especially for disturbances larger than 1000MW (see section 4.5)

Frequency Quality / Inertia

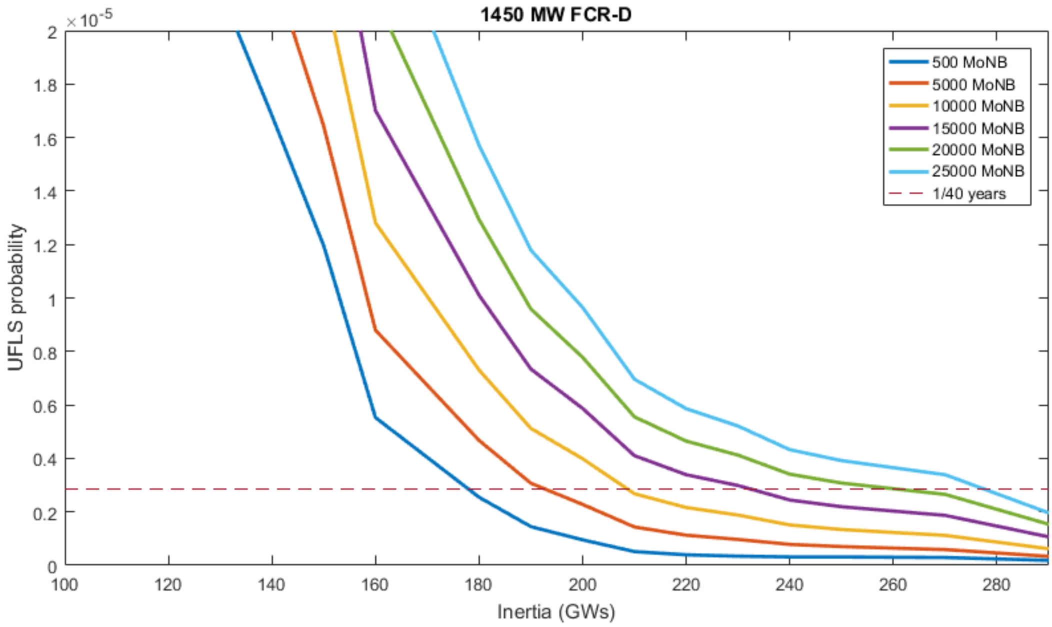


Figure 21:UFLS probability as function of inertia and FCR-D level. Note that the disclaimer in section 1.5 is applicable.

Figure 21 shows the impact of inertia on the UFLS probability for different levels of frequency quality. The figure shows that the UFLS probability increases more quickly for combinations of low inertia levels. For low frequency quality the UFLS probability increases even faster.

6 Application of methodology of UFLS risk

6.1 Assessing impact of combinations of MoNB and amount of FCR-D on UFLS risk

Table 3 shows that for the period from April 2015 to March 2016, the average UFLS risk level was once in 38 years, resulting from 8146 MoNB in this period and approx. 1800MW of FCR-D on average. Table 5 shows the impact on the average UFLS risk if the amount of FCR-D and frequency quality (MoNB) varies. Similar tables could be produced for individual hours.

Table 5: Impact of amount of FCR-D and frequency quality (MoNB) on UFLS risk for April 2015 to March 2016. Note that the disclaimer in section 1.5 is applicable.

MoNB	950 MW	1050 MW	1150 MW	1250 MW	1350 MW	1450 MW	1550 MW	1650 MW	1750 MW	1850 MW
500	1.7	3.1	6.6	17	29	39	46	56	67	65
5000	1.3	2.3	4.7	11	18	24	29	36	44	44
10000	1.0	1.8	3.5	7.3	12	16	20	25	30	31
15000	0.8	1.4	2.7	5.5	8.7	12	15	19	23	24
20000	0.7	1.2	2.3	4.4	6.8	9.5	12	15	18	19
25000	0.6	1.0	1.9	3.7	5.7	7.9	10	12	15	16

6.2 Target for UFLS risk from Guidelines on System Operation

GL SO art. 153 defines that it shall be the aim to reduce the probability of insufficient FCR to below or equal to once in 20 years[52]. Cases of insufficient *upward* FCR will trigger UFLS. Assuming an equal split between probability of insufficient *upward* and *downward* FCR, a target of 'once in 40 years' can be applied for *upward* FCR and consequently for UFLS. The calculated UFLS risk could therefore be compared with a target of 'once in 40 years', which is done by colouring the cells in Table 5.

6.3 Finding the socio-economic optimum for UFLS risk

Table 5 shows the UFLS risk for different combinations of frequency quality and amount of FCR-D. Theoretically, the socio-economic optimal combination could be found by converting these parameters in socio-economic costs and finding the minimum. The FQ2 project has made an attempt for finding the socio-economic optimum for fixed MoNB. For this purpose, the socio-economic costs of additional reserves and UFLS risk have been evaluated.

The ***socio-economic costs of reserves*** have been estimated by market modelling experts of Fingrid and Svk. The resulting socio-economic reserve cost per MW per hour were €0.76±100% (Fingrid, applicable to the Nordic system) and €4±100% (Svk, applicable to SE2). (see Annex C for details). Based on these figures, we apply a range from 0.5 to 5 Euro per MW per hour for the socio-economic cost of upward FCR-D[53].

[52] Article 153 (FCR dimensioning): *(c) […] all TSOs of the synchronous area shall have the right to define a probabilistic dimensioning approach for FCR taking into account […], with the aim of reducing the probability of insufficient FCR to below or equal to once in 20 years;*

[53] The optimisations have been done for a single number of minutes outside the standard frequency range. The amount of FCR-N and aFRR influence both this number and the socio-economic cost and may also need to be considered.

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The ***socio-economic costs for reduced UFLS risk*** have been estimated based the multiplication of

- an assumed average duration of an outage caused by automatic UFLS of 3 hours;
- an assumed share of 2.5% load that is shed during a UFLS event; and
- the assumed Value of Lost Load for the affected customers of 10 Euro/kWh;
- the load at the time of the UFLS event.

Based on these assumptions, the expected cost of one UFLS event will be 750 Euro per MW consumption. Since the three assumptions are highly inaccurate, a band of 375-1500 Euro per MW consumption is considered. After multiplying with the load at the time of the UFLS event, this would result in 11-45 million Euro in case of a minimal Nordic load (30GW) and 26 and 105 million Euro in case of a maximal Nordic load (70GW).

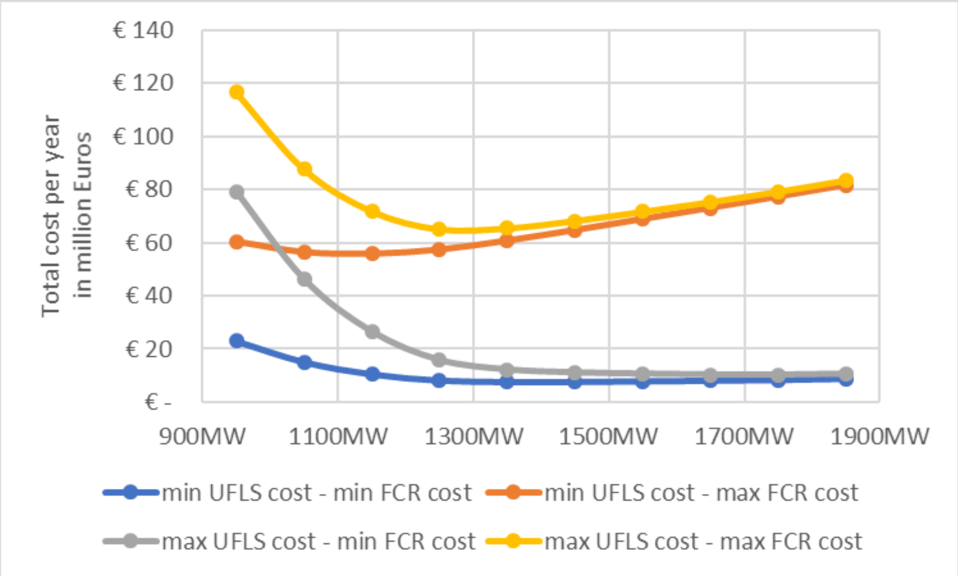

Figure 22 Sensitivity analysis for total yearly socio economic cost for minimum and maximum inertia levels, for a frequency quality of 10,000 minutes outside the normal band Note that the disclaimer in section 1.5 is applicable.

Figure 22 shows the total socio-economic cost as function of the FCR-D level, for the different ranges explained above. The figure shows that FCR-D level with the lowest socio-economic cost is between 1150 and 1750MW. Since this large range is not very meaningful in practice, it can be concluded that with the current accuracy of the input parameters, it is not feasible to provide a sensible value for the optimal FCR-D level from a socio-economic perspective.

Alternatively, some indication can be provided. E.g. for the 2020 forecast situation with 10,000 MoNB and 1250MW of FCR-D, 100MW of additional FCR-D would increase the socio-economic cost with [0.5-5] million Euro/year and would reduce the UFLS risk from 1/6.6 year to 1/10 year, of which the socio-economic benefit is estimated to 1.9-7.5 million Euro/year. I.e. at this frequency quality, increasing the amount of FCR-D will likely be socio-economically efficient.

6.4 Dimensioning reserves by using UFLS risk

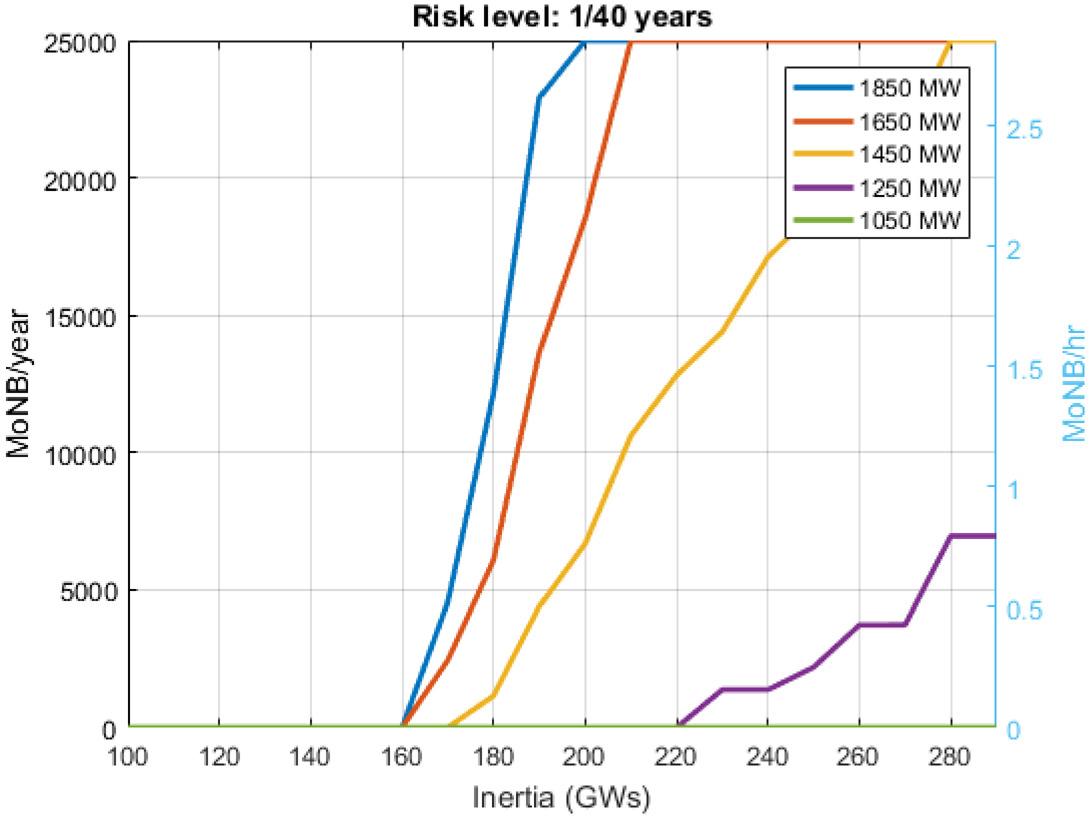

Figure 23: Relationship between Inertia and frequency quality (and assumptions in Table 2) that result in UFLS risk of once in 40 years, for different amounts of FCR-D. Note that the disclaimer in section 1.5 is applicable.

Section 6.2 suggests a target UFLS risk of once in 40 years. Figure 23 shows for this target level the required MoNB for each inertia level, the figure provides lines for different amounts of FCR-D. Figure 23 could be used in the planning phase for finding the right target of MoNB for specific hours or times of year, based on the forecasted inertia. MoNB could be controlled with different measures including FCR-N and aFRR. If the relationship between FCR-N/aFRR reserves levels and MoNB is known, dimensioning of these reserves could be done based on a constant target for UFLS risk. At this moment, the missing link for this analysis is the relationship between MoNB and FCR-N and aFRR.

The relationship between Inertia and required MoNB to reach the UFLS target in Figure 23 allows the Nordic TSOs to set differentiated criteria for MoNB for different times of the year (seasons, days, hours). This could be used for dimensioning of aFRR and FCR-N.

7 Framework for measurement and reporting

This chapter proposes a framework for measurement and reporting on the frequency quality in the Nordic system.

7.1 Different situations and processes

Frequency quality is determined by the imbalances in the system and the effectiveness of the process that mitigates the imbalance. Traditionally *stochastic imbalances* and *disturbances* were the major cause of imbalances. The introduction of electricity markets introduces *imbalances caused by forecast errors* and additional *deterministic imbalances*[54] at hour shifts. The different types of imbalances influence the frequency quality in differently:

- *Disturbances:* incidentally and within seconds;
- *Stochastic:* continuously in normal operation and within minutes;
- *Deterministic:* at given times (e.g. hour shifts) and within minutes;
- *Imbalances caused by forecast errors* cause differences between forecasted and measured generation of settlement periods, i.e. one hour (in future 15 minutes). The influence on the frequency quality is determined by quality the FRP process.

7.2 Objectives

The objectives of reporting are:

- To follow the compliance with the frequency quality defining and target parameters;
- To identify trends in frequency quality;
- To evaluate the effectiveness of the Frequency Containment Process (FCP) and the Frequency Restoration Process (FRP);
- To comply with the regulatory requirements on providing information on frequency quality, especially art. 131-134 and 185 in the European Guideline on electricity Transmission System Operation (GL SO);

7.3 Reporting frequency

At this moment, Fingrid prepares an annual frequency report, the f-report. Every week, Statnett's control centre prepare a frequency statistics report, which include e.g. the Minutes outside the normal band and information on FRR activation. Art. 185 of the GL SO requires that the Nordic TSOs shall at least four times per year present the frequency indices mentioned in article 133.

The FQ2 project team recommends implementing an automated on-line reporting tool that can present on-line the required graphs and tables for the time period and resolution, requested by the user of the tool, similar to Statnett's data warehouse Innsikt[55]. The frequency data shall be uploaded daily.

As a short term solution, every three months a frequency quality report can be issued. The document could add the latest monthly values for the different indices to the history of the last 5 years, similar to Fingrid's annual f-report[56]. The preparation of this document could be highly automated.

[54] Other deterministic imbalances such as the imbalances at times of a tariff change already existed.
[55] For Innsikt frequency data with 1s resolution is available at this moment. Innsikt can provide a wide variation of parameter calculations and representations in graphs.
[56] report Frequency quality analysis for year 2015, Fingrid, 16.8.2016

7.4 Proposed Frequency indices for a reporting framework

Table 6 provides an overview of the proposed frequency indices for monitoring frequency quality at all times. Table 7 provides an overview of the suggested frequency indices for each disturbance with an imbalance larger than 200MW. Section 3 in Annex D shows an example of such a report. Table 6 and Table 7 include:

a) *Definition of the index:* Detailed definitions and calculating methodology are defined in Annex D.
b) *Required resolution of the frequency data* that shall be used for calculating the frequency index. E.g. A resolution of 1s means that samples of every 1s values shall be used. The samples shall represent the average of the frequency in this 1s period, e.g. by taking the average of ten 0.1s values;
c) *For which process the frequency index would be a quality indicator*: Frequency indices could be an indicator of the performance of the Frequency Containment Process (FCP), the Frequency Restoration Process (FRP), number of activations of FCR-D, number of Under Frequency Load Shedding (UFLS) events, deterministic imbalances and UFLS risk;
d) *Reference* to:
    - Guideline on System Operation (GL SO) if the GL SO requires that the TSOs shall include this frequency index in their three-monthly report[57];
    - FCP: indices defined and applied by the FCP project;[58]
    - f-report: indices defined and used by Fingrid in their f-report[59];
    - FQ2: in case of an index suggested by the FQ2 project in addition to the previous sources.

Most indices are collected from previous work, the FQ2 project added the *frequency step around the hour shift* that could reflect deterministic imbalances and the *UFLS risk* that provides an indication of the security of supply with respect to frequency quality as perceived by the customers. For disturbances, FQ2 defined the *steady state frequency* and an index that provides an indication of *damping* of frequency after a disturbance.

[57] GL SO articles 185(4) and 131.
[58] ‘Frequency Quality Indices in FCP project, Version 2, Nordic Analysis Group (NAG), 14 December 2015
[59] report Frequency quality analysis for year 2015, Fingrid, 16.8.2016

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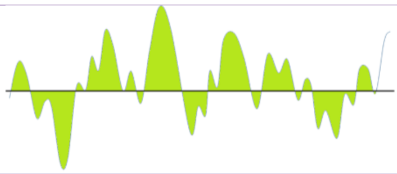
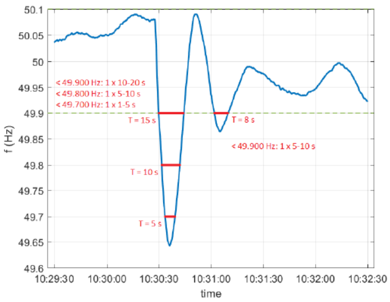
Table 6: Overview of the proposed frequency indices for monitoring frequency in normal and alert state ([a], [b], [c] and [d] refer to the description above.

	Frequency Indices	Definition[a]	Resolution f-data[b]	Indicator for[c]	Reference[d]
1	Average frequency	$\bar{f} = \frac{\sum_{i=1}^{n} f_i}{n}$	1s 15min	Time control process	GLSO GLSO
2	Standard deviation of frequency	$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(f_i - \bar{f})^2}$	1s 15min 1min	Deviation from 50Hz, FCP, FRP	GLSO GLSO FQ2
3	Frequency area		0.1s	Deviation from 50Hz, FCP, FRP	FCP
4	1- ,5- ,10- , 90-, 95- and 99-percentile of frequency	The n-percentile of frequency indicates the frequency below which n% of the frequency of all samples of the observation period fall.	1s 15min 1min 5min	Deviation from 50Hz, FCP, FRP	GLSO GLSO FQ2 FQ2
5	Time outside 49.9-50.1Hz (positive and negative)	Count samples that are below 49.9Hz or above 50.1Hz	1s 1min	Follow-up target for MoNB, FCP, FRP	GLSO GLSO
6	Number of frequency deviations (positive and negative) with a duration of 0-1s, 1-5s, 5-10s, 10-20s, 20-40s, 40-60s, 1-3min		0.1s	FCP, FRP	f-report
7	Number of frequency deviations (positive and negative) with a duration of 1-3min, 3-5min, 5-10min, 10-15min and > 15 min		1 min	FRP	FQ2
8	Number of threshold crossings (49.9 and 50.1Hz)	Counts the number of 1s samples for which frequency is below 49.9Hz and previous sample is above 49.9Hz (equivalent for 'above 50.1)	0.1s	FCP, number of activations of FCR-D	FCP
9	Time outside 49.0-51.0Hz (positive and negative)	Count 1s samples that are below 49.0Hz or above 51.0Hz	1s	UFLS, FCP, FRP	GLSO
10	df>200mHz, not restored with 15 min	Count number of events in which a 1s sample is below 49.8Hz and all 1s samples in the 15 minutes afterwards are below 49.9Hz (equivalent for above 50.2/50.1Hz)	1s	FRP	GLSO

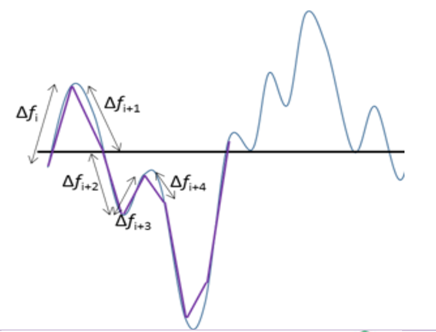
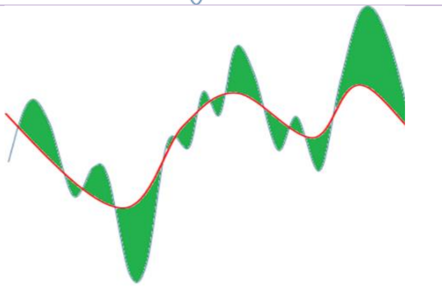
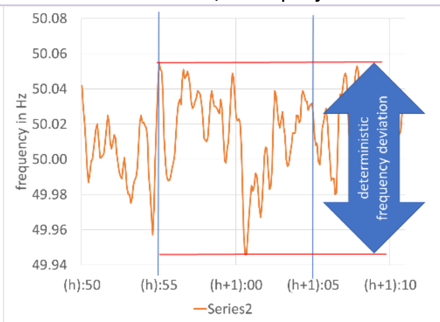
	Frequency Indices	Definition[a]	Resolution f-data[b]	Indicator for[c]	Reference[d]
11	Length of frequency path		0.1s	FCP, Frequency oscillations	FCP
12	Amount of the frequency oscillation		0.1s	Frequency oscillations	FCP
13	Quarters outside FRCE target level 1 and level 2, (negative and positive FRCE)	Target level 1 and level 2 indicate a freqeuncy deviation that may be exceeded in 30% (level 1) or 5% (level 2) of time. Target level 1 and level 2 discussed in the SOA/LFCR project.	15 min	FRP?	GLSO
14	frequency step around the hour shift: 1%, 5%, 10%, 50%, 90%, 95% and 99% percentile		1s	deterministic frequency deviation	FQ2
15	UFLS risk	See chapter 5 of this report	1s	FCP, FRP, Frequency quality	FQ2
16	number of events for which the FRCE exceeded 60 % of the reserve capacity on FRR and was not returned to 15 % of the reserve capacity on FRR within 15 min (negative and positive FRCE)	*This indicator will only be applicable in case of splitting of the Nordic Synchronous area in different LFC Areas. Until then, FRCE is measured in Hz and is difficult to compare with reserve capacity, measured in MW.*			GLSO

Table 7: Overview of the proposed frequency indices for monitoring frequency in normal and alert state ([a], [b], [c] and [d] refer to the description above Table 6.

	Frequency Indices	Definition[a]	Resolution f-data[b]	Indicator for[c]	Reference [d]
1	date and time	Central European Time	0.1s		f-report
2	f_{start}	frequency at time of disturbance: at which df/dt> 0.035Hz/s	0.1s		f-report inertia1
3	$f_{extreme}$ (or f_{nadir})	Minimum frequency for negative imbalance or maximum frequency for positive imbalance	0.1s	How close to UFLS	f-report inertia1
4	Instantaneous frequency deviation Δf	$\Delta f = \lvert f_{extreme} - f_{start} \rvert$	0.1s		f-report
5	Time to *maximum instantaneous frequency deviation* Δt	$\Delta t = \lvert t_{extreme} - t_{start} \rvert$ in which t_{start} is time at which f_{start} takes place and $t_{extreme}$ time at which $f_{extreme}$ took place	0.1s		f-report inertia1
6	ΔP	Instantaneous imbalance caused by the disturbance	0.1s	Size of incident	f-report
7	E_k	Inertia just before the incident	0.1s	System at time of incident	f-report
8	cause	Reason for the trip	0.1s		f-report
9	$f_{steady\ state}$	Proxy: average of frequency between 90 and 150s after the disturbance	0.1s	Amount of FCR-D	FQ2
10	$\Delta f_{steady\ state}$	$\Delta f_{steady\ state} = \lvert f_{steady\ state} - f_{start} \rvert$	0.1s	Amount of FCR	FQ2
11	$f_{extreme2}$	Second extreme in the other direction as $f_{extreme}$	0.1s		FQ2
12	$f_{extreme3}$	Third extreme in the same direction as $f_{extreme}$	0.1s		FQ2
13	Damping of frequency after disturbance	$\left\lvert \frac{f_{extreme3} - f_{extreme2}}{f_{extreme2} - f_{extreme1}} \right\rvert$	0.1s	damping	FQ2
14	Frequency Bias Factor	$FBF = \frac{\Delta P}{\Delta f_{steady\ state}}$	0.1s	Stiffness of system	FQ2

7.5 Required and available frequency data

For frequency quality indices related to disturbances, frequency data on a resolution of 0.1s shall be used. Since in a few seconds after disturbances, the frequency is not the same in the Nordic system, the location of the frequency measurement shall be also defined. The FQ2 project recommends a central place in the Nordic system, e.g. the Midskog substation in Sweden. Another option might be using some kind of average value for four PMU measurements from each country. Most importantly the measurements shall be GPS synchronized, i.e. not SCADA data which has inaccurate timestamp. This leads to the conclusion that the data used should be PMU-data. At this moment, only Fingrid has frequency data available for continuous operational use on a resolution of 0.1s[60].

For most other frequency quality indices, frequency data with a 1s resolution is sufficient and does not require a specific measurement location.

[60] All TSOs measure and store frequency data, but all at different resolution: Fingrid: PMU data on ≤0.1s resolution; Svk: SCADA data on 5s resolution; Statnett: SCADA data on 1s resolution (PMUs can be read incidentally); Energinet.dk: 1s in SCADA system, 20ms in PMU (only available for two months, selections can be archived)

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8 Results and Conclusions, Complications and Recommendations

8.1 Results and Conclusions

A probabilistic methodology that can be applied to estimate the risk for Under Frequency Load Shedding (UFLS risk) has been established in the project. Seven parameters have significant influence on the UFLS risk: Inertia, FCR-D response time and volume, Emergency Power (EPC) provided by HVDC links, self-regulation of loads, size and probability of disturbances, threshold of first stage of UFLS. The methodology estimates the UFLS risk for a single hour or even minute, but can also be used for estimating figures of UFLS risk over a complete year, both historical and in the future. In addition, the methodology can also be used for operational purposes.

UFLS risk is largely found in periods with frequency between 49.85-49.95Hz. The main reason for UFLS risk at high frequencies is that the response of the implemented FCR-D is too slow to cope with the lower inertia situations. In addition to this, between 49.85-49.90Hz normal imbalances are often mitigated by a misuse of disturbance reserves. Consequently, insufficient reserves may be left for preventing UFLS. It shall be noted that in the previous century, FCR-D was designed and mainly used for occasional disturbances, i.e. a frequency excursion below 49.90Hz was likely a disturbance. This changed dramatically over the last decades and currently FCR-D is mainly activated for mitigating other imbalances than disturbances, resulting in a significant increase of UFLS risk.

The calculated UFLS risk can be compared with the ‘probability of insufficient FCR to be below or equal to once in 20 years’ that is referred to in the European Guidelines on System Operation. Since the ‘once in 20 years’ covers both upward and downward regulation, a pragmatic target for UFLS risk (insufficient upward FCR) is ‘once in 40 years’.

The UFLS risk has been simulated for an entire year (April 2015-March 2016), based on a number of conservative assumptions. The accumulated UFLS risk during this period is far larger than the ‘once in 40 years’ target. However, if the dimensioned amount of FCR-D (1250MW) is used instead of the actual available FCR-D (on average 1800MW), the UFLS risk is in the same order of magnitude as the target.

Sensitivity studies were performed in order to see the impact of different parameters to the end results. Some conclusions were made: EPC and self-regulation of loads have similar impact. This can be explained with the tested situation where the volume and activation speed of self-regulation and EPC was approximately the same. This leads to the conclusion that fast disconnection of loads may have similar impact as EPC.

Sensitivity studies further show that common cause failures may have a significant effect on the estimated UFLS risk, but the influence of changing risks due to e.g. new HVDC links can be even higher. For improving the quality of the results for future scenarios, the forecasts of the disturbances, especially for disturbances larger than 1000MW shall be improved.

As a result from the studies for a desired UFLS risk and fixed amount of FCR-D, a relationship between Minutes outside normal frequency band (MoNB) and the level of inertia in the power system is given. This can be used for planning the purchase of FCR-N and aFRR if the level of inertia can be forecasted.

The socio economic cost for UFLS risk has been estimated. The estimation is based on an assumed average duration of an outage caused by automatic UFLS, assumed average share of load shed during a UFLS event and the assumed Value of Lost Load for the affected customers. The UFLS risk can be influenced by FCR-D and/or by affecting the frequency quality (minutes outside the 49.9-50.1Hz band, influenced by FCR-N and aFRR). Theoretically it would be possible to find the optimal UFLS risk for a given frequency quality by combining the cost curves of socio-economic cost for UFLS risk and cost curves of socio-economic cost for reserves. However, the determined optimal UFLS risk has a limited accuracy since some of the currently

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available input parameters have a limited accuracy. Nevertheless, the calculations can provide some insight in the orders of magnitude: For the 2020 forecast situation, with 10,000 MoNB and 1250MW of FCR-D, 100MW of additional FCR-D would increase socio-economic cost with 0.5-5 million Euro/year and would reduce the UFLS risk from once per 6.6 years to once per 10 years, of which the socio-economic benefit is estimated to be 1.9-7.5 million Euros per year.

The proposed frequency quality reporting framework will report on frequency deviations due to the different imbalances separately. The f-report prepared annually by Fingrid is used as a basis. Other inputs are the Nordic report "Future System Inertia" for the quality parameters during frequency disturbances and the indices developed by the FCP project (Revision of Frequency Containment Process). FQ2 developed additional new indices related to both the damping of frequency and the steady state frequency after frequency disturbances. Additionally, FQ2 tested a measure on deterministic frequency deviations. The FQ2 project team suggests implementing an automatized on-line reporting tool for some indices, but as a first step a report every three month as required in Guideline on System Operation can be issued.

8.2 Challenges (and complications)

The focus of the Frequency Quality 2 was on a frequency quality framework. The Frequency Containment Process has been covered by another project. However, the two issues are highly interlinked and shall be optimised simultaneously.

Frequency Quality 2 project developed a method for defining the target for MoNB and the volume of FCR-D. FCR-N and aFRR could be dimensioned in order to meet the MoNB target. One challenge is that there is currently no harmonised implementation of FCR-N and FCR-D in Nordics. This means that the responses of FCR are different, and the FCR is therefore at the moment not seen as an efficient "tool" for this kind of optimization. On the other hand aFRR is more harmonised, so that could be utilised more in near future. In future, a more well defined relationship between improved FCR-N and aFRR has to be found.

The methodology for calculating UFLS risk has been built on the so-called RaR model from 2011. More recent studies ("60s project") show that units all respond differently and that the RaR model needs to be updated.

8.3 Recommendations

The probabilistic methodology estimates the UFLS risk based on a number of assumptions. It provides good insight in the importance of the seven parameters that affect UFLS risk. FQ2 recommends improving the assumptions and consequently the accuracy of the UFLS risk estimates by:

- Improving the RaR model, based on information gained by e.g. the FCP project;
- Improving input on disturbance probability, based on better disturbance statistics, especially for disturbances of new HVDC links and other load and production disturbances larger than 1000MW;
- Improving knowledge on the behaviour of system, consumption and productions if the frequency is below 49.5Hz, by studying cases in which low frequencies occurred in detail. These situations could include situations in island mode;
- Improving assumptions on self-regulation of load, based on input from the STRI project or a different study;
- Improving information about Emergency power, based on completion of an overview prepared by Fingrid;
- Improving for the input to the socio-economic optimisation, including socio-economic cost of FCR-D, VOLL and duration of an UFLS event. Alternatively, standard values can be agreed;

- Further improve the model implementation (see annex A) for details.

FQ2 recommends implementing a frequency quality reporting framework, for after the fact analysis, compliance with the reporting requirements in the System Operation Guidelines and for real time use. This frequency quality framework shall include:

- UFLS risk since this index reflects Security of Supply better than MoNB;
- Indices developed by FQ2 for steady state frequency, deterministic frequency deviation and damping of frequency after disturbance;
- Indices developed by the FCP project;
- Indices required by the System Operation Guideline.

FQ2 recommends using the results of the FQ2 project in planning and operations for:

- *Planning:* Dimensioning reserves based on the forecasted inertia and a target UFLS level of once in 40 years. As input for this, FQ2 results include the relationship between inertia, MoNB and FCR-D. A relationship between MoNB and FCR-N and aFRR is to be developed;
- *Real Time* operation evaluation of UFLS risk. This requires tools that provide information on e.g. availability of EPC, inertia, FCR-D;
- After the Fact evaluation of disturbances.

Since EPC and fast disconnecting load has a major impact on the UFLS risk, FQ2 recommends exploring the possibilities of using these measures more systematically, by:

- Confirming the availability and correct operation of the EPC on different HVDC links;
- Optimising the distribution and settings of the EPC capacity over the different HVDC links;
- Safeguarding the future availability of EPC.

FQ2 developed an interpretation of the Alert state based on a proxy for steady state frequency. FQ2 suggest applying this definition.