REPORT

# FCR-D design of requirements

## VERSION 1 - 5 JULY 2017

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# Contents

## ABBREVIATIONS AND SYMBOLS

### Abbreviations

| | |
|---|---|
| EPC | Emergency Power Control |
| FCP | Frequency Containment Process |
| FCR | Frequency Containment Reserve |
| FCR-D | Frequency Containment Reserve for Disturbances |
| FCR-N | Frequency Containment Reserve for Normal operation |
| HVDC | High Voltage Direct Current |
| KPI | Key Performance Indicator |
| PID-controller | Proportional-Integral-Derivative-controller |
| pu | Per unit |
| RoCoF | Rate of Change of Frequency |
| SISO | Single Input Single Output |
| TSO | Transmission System Operator |

### Symbols

| | |
|---|---|
| $A_m$ | Amplitude margin (also gain margin) |
| $d$ | Disturbance signal |
| $E_{kin}$ | Kinetic energy |
| $f_0$ | Nominal frequency |
| $F(s)$ | Control unit (transfer function) |
| $G(s)$ | Power system (transfer function) |
| $G_{max}$ | Gate saturation upper limit |
| $G_{min}$ | Gate saturation lower limit |
| $R_{open}$ | Gate servo ramp-rate limit for opening |
| $R_{close}$ | Gate servo ramp-rate limit for closing |
| $H_x$ | Inertia constant of machine $x$ |
| $H$ | Inertia constant of the system |
| $j$ | Complex number |
| $k$ | Frequency dependency of loads |
| $K_d$ | Derivative part (constant in PID controller) |
| $K_i$ | Integral part (constant in PID controller) |
| $K_p$ | Proportional part (constant in PID controller) |
| $L(s)$ | Loop gain (transfer function) |
| $M_s$ | Stability margin limit |
| $P$ | Active power |
| $r$ | Euclidian stability margin |
| $s$ | Laplace operator |
| $t$ | Time |
| $T_f$ | Filter time constant for derivate part (in PID controller) |
| $T_g$ | Gate servo time constant |
| $T_w$ | Water time constant |
| $P_e$ | Electrical power |
| $P_m$ | Mechanical power |
| $S(s)$ | Sensitivity function (transfer function) |
| $S_n$ | Rated power |
| $X$ | Identification number of a machine |
| $y$ | Output signal |
| $Y_0$ | Loading of the unit |
| $\Delta f$ | Frequency deviation |
| $\Delta P_{disturbance}$ | Dimensioning disturbance |
| $\varphi_m$ | Phase margin |
| $\theta$ | Angle |
| $j\omega$ | Complex angular frequency |

# 1. INTRODUCTION

Frequency stability is the ability of a power system to maintain steady state frequency following a severe disturbance, resulting in a significant imbalance between power production and consumption [1]. After a sudden change in either power production or consumption, frequency of the system begins to change. Initially, the surplus or deficit of power is balanced by the inertia of the system, which is the resistance to frequency change. In order to achieve stable frequency, units connected to the power system have to adjust their power to match the change in power production or consumption. The primary reserve is the active power system service to automatically handle such severe disturbances and is often activated proportionally to the frequency deviation. However, this is valid in steady state and does not specify the dynamic response, which has a great impact on the frequency stability. Rate of change of frequency (RoCoF) is the time derivative of the frequency and is an important measure when it comes to primary frequency control. The highest/smallest value, depending on the type of imbalance, is most often achieved directly after an active power disturbance and is proportional to the power change and inversely proportional to the inertia constant (or kinetic energy) of the system.

The primary frequency control in the Nordic synchronous area is called the Frequency Containment Process (FCP) which consists of two parts, Frequency Containment Reserve for Normal operation (FCR-N) and Frequency Containment Reserve for Disturbances (FCR-D). The existing requirement on FCR-D states that, after a step in frequency to 49.5 Hz the reserve shall respond by 50 % increase of its steady state capacity in 5 s and deliver full response after 30 s [2]. The total FCR-D capacity procured shall be equal to the single event that can cause the largest sudden power imbalance, the dimensioning fault, deduced by 200 MW (assumed self-regulation of loads due to their frequency dependent characteristics). For the time being, the dimensioning incident is the largest production unit in the system. In this work, the focus is on the frequency minimum and the requirement on FCR-D service. The response from FCR-D is assumed to be symmetric for over and under frequency.

## 1.1 BACKGROUND OF THE PROJECT

Frequency stability imposes boundaries where the frequency should be kept within at all times. The System Operation Guideline states that the default value for the maximum instantaneous frequency deviation is 1000 mHz in the Nordic synchronous area [3]. Furthermore, automatic load shedding occurs from 48.8 Hz which shall be avoided [2]. By analysing the existing requirements on FCR-D it has become clear that current FCR-D alone would not keep the minimum frequency above 49.0 Hz. However, emergency power control (EPC) functions are used on the HVDC interconnections and starts to ramp up/down their power at different triggering levels [2]. In addition, some lower priority loads (like pumps) are disconnected with some delay if the frequency goes below 49.4 Hz [2]. Furthermore, typically more FCR-D is supplied than the minimum procured capacity.

After a sudden power deficit (surplus) the system frequency will continue to decrease (increase) until balance is restored between power consumption and production. Thus, the FCR (Frequency Containment Reserve) providing units have to make sure that the power balance is restored before 49.0 Hz (51.0 Hz). A typical dimensioning incident is the nuclear power unit Oskarshamn 3 with 1450 MW which is the dimensioning power deficit considered in this work. In a low inertia situation, if Oskarshamn 3 trips, in practice the power balance must be met within approximately 5 seconds in order to maintain the frequency above the limit. Thus, there is a need to revise the existing requirements on FCR-D in order to maintain frequency stability in the current and future system. In addition, the previous project "*Measures to mitigate frequency oscillations with a time period of 40-90 s"* identified drawbacks with the existing implementation of FCR-N. Therefore, it was decided to take a holistic approach of the frequency containment process in the Nordic synchronous area. The FCP-project (Revision of the Nordic Frequency Containment Process) addresses the design of FCR and has been jointly carried out by the Nordic TSOs, Energinet, Fingrid, Statnett and Svenska kraftnät.

## 1.2 FRAMEWORK FOR THE WORK

This report deals with the FCR-D in order to design requirements that fulfil specified system needs. The work is limited to current hydro power units as the reference model. However, the requirements should be technology neutral. It is assumed that if the requirements are feasible for hydro power, other technologies like thermal power and different types of load are able to adapt to the requirements as well.

Frequency dependency of loads is given in the framework but no voltage dependency is included. However, in reality contribution from voltage dependency may not always be negligible. In addition, no interactions between different providers of FCR-D are to be included as the system is viewed as a single entity.

The current[1] level of inertia and the low inertia value used in the development of the requirements will not give rise to too high initial rate of change of frequency (from generators rate of change of frequency withstand capability point of view). Therefore RoCoF is not considered in this work.

## 1.3 GOALS

This work aims at developing requirements on FCR-D in order to maintain frequency stability. The requirements shall

- be functional and testable locally at each FCR provider
- meet the system needs in terms of dynamic response to keep the frequency within boundaries (49.0 and 51.0 Hz) for the dimensioning incident
- meet the specified largest steady state frequency deviation
- ensure stability in a control perspective[2]

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[1] 2017

[2] asymptotically stable, that is frequency converges to an acceptable operating point

## 1.4 OUTLINE

Section 2 provides a theoretical overview of control systems with focus on stability and the concept of performance as rejection of a disturbance. In Section 3, used models are described. The FCR-D requirements are developed in Section 4, including comprehensive explanations and motivations. In section 5, the test procedure for verifying unit's compliance with the designed requirements is outlined. Future work is provided in Section 6 as identified issues with the developed requirements as this project was delimited in scope, time and resources. Conclusions are drawn in Section 7 and references can be found in Section 8. Appendixes are listed in Section 9.

# 2. THEORETICAL BACKGROUND

General theory of control systems is provided in this section. Stability is viewed in a linear way and the concept of performance in terms of rejection of a disturbance is briefly explained.

## 2.1 STABILITY

The term stability is used in terms of asymptotic stability which means that there exists no initial condition or no bounded input signal that drives the output to infinity.

Consider the SISO feedback system shown in Figure 1. In the figure, *F(s)* is the control process, *G(s)* is the system, *d* is a disturbance signal entering the system, *y* is the output of the closed loop system and *s* is the Laplace operator.

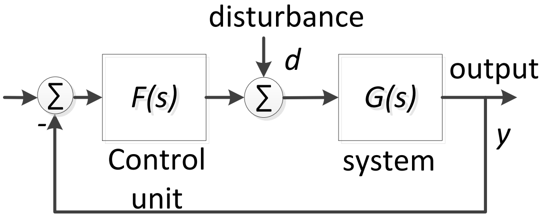

**FIGURE 1: OVERVIEW OF A FEEDBACK SYSTEM**

One would like to be able to determine whether or not the closed loop system is stable. The mathematical framework of transfer functions provides an elegant method, which is called *loop analysis*. The basic idea of loop analysis is to trace how a sinusoidal signal propagates in the feedback loop, this by investigating if the propagated signal grows or decays. One way to analyse stability is by using the Nyquist criterion which in turn uses the loop gain. The loop gain is defined as

$$L(s) = F(s)G(s) \tag{2.1}$$

The loop transfer function, also named sensitivity, is defined as

$$S(s) = \frac{1}{1 + L(s)} \tag{2.2}$$

and describes the propagation of a signal through the loop, i.e. how the output amplifies through the loop.

The amplification of a signal is determined by the denominator. Whether the signal grows as it is phase shifted by $180^o$ (the signal has opposite sign) in the loop determines if the system is stable or not. The point where a signal has phase shift and its amplitude remains corresponds to where to denominator is equal to zero i.e.

$$L(s)|_{s=j\omega_0} = -1$$

thus the point -1 is of interest together with the loop gain.

The Nyquist curve is the loop gain, that can be plotted in the complex plane, with the Laplace operator *s* replaced by the complex value *jω* and the angular frequency ω varying as shown in Figure 2. The system is asymptotically stable if the Nyquist curve does not encircle the point (-1, 0). This holds true for simple enough systems (loop gains) as one could in theory cross the negative real axis twice to the left of the point (-1, 0) and still not encircle this point. Note that this criterion is only valid if the loop gain is at least marginally stable i.e. no poles in the right half plane. Basically, at the point where the Nyquist curve has a phase shift of 180° the loop transfer function should be smaller than one. For a more detailed description readers are referred to [4] and textbooks in the field of linear control theory. In practice it is not enough that a system is stable. There must also be some margins of stability that describe how stable the system is and its robustness to perturbations. A stability margin is introduced by a distance between the Nyquist curve and the point (-1, 0). It can be specified in terms of amplitude margin[3] (also known as gain margin), ($A_m$), phase margin[4], ($\varphi_m$), and the smallest Euclidian distance, *r*, between the Nyquist curve and the point (-1, 0) (referred to as the stability margin).

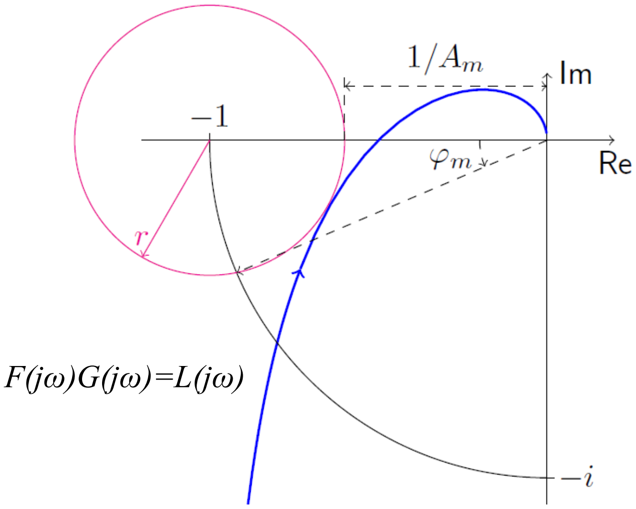

**FIGURE 2: NYQUIST PLOT. NOTE THAT THE INDICATED PHASE AND GAIN MARGIN ARE HERE IMPOSED BY THE CIRCLE. THE BLUE CURVE HAS LARGER AMPLITUDE AND PHASE MARGINS THAN GUARANTEED BY THE EUCLIDIAN DISTANCE.**

Specifying the Euclidian norm guarantees that the amplitude and phase margin become

$$A_m \geq \frac{1}{1-r} \tag{2.3}$$

$$\varphi_m \geq 2\,sin^{-1}(\frac{r}{2}) \tag{2.4}$$

A drawback with gain and phase margins is that it is necessary to give both of them in order to guarantee that the Nyquist curve is not close to the critical point. Moreover, phase and amplitude

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[3] the factor by which the loop gain can be increased until the Nyquist curve intersects with the point (-1, 0)

[4] angle between the negative real axis and the point where the curve crosses a circle centred in origin with unity radius

margins do not guarantee a certain distance to the point (-1, 0). Note that none of the mentioned margins guarantee closed loop stability themselves – the point (-1, 0) may be encircled without entering the r-circle, and both the unit circle and the negative real axis may be crossed multiple times. However, it can be assumed that the loop gain is simple enough so that such margins ensure stability.

Furthermore, the stability margin limits the sensitivity function as follows

$$|S(s)| \leq \frac{1}{r} = M_s \tag{2.5}$$

as the sensitivity function is the loop transfer function. This comes from the fact that the denominator in the sensitivity function is the Euclidian distance between the loop gain and the point (-1, 0). Thus, keeping the supremum norm ($max_{\forall\omega}|S(s)|$) below one over *r* ensures the loop gain not to amplify more at any particular frequency. If nominal stability is fulfilled, i.e. the point (-1, 0) in the Nyquist plane is not encircled, it implies robust stability and implies uncertainties to be allowed in the plant or controller.

**Main point:** To ensure robust stability is equivalent to check either the Nyquist curve (2.1) or the maximum sensitivity (2.5).

## 2.2 PERFORMANCE

The transfer function from a disturbance to the output is given by

$$\frac{G(s)}{1 + F(s)G(s)} d = S(s)G(s)d = y \tag{2.6}$$

Thus, the transfer function from a disturbance is the sensitivity function times the transfer function of the system. Therefore, the sensitivity function not only matters in the stability analysis but also plays an important role in how a disturbance propagates in the system. The disturbance signal can be modelled in different ways - deterministic or stochastic.

# 3. MODEL DESCRIPTION

This section provides a description of the power system (*G(s)*) and the control unit (*F(s)*) models used. The power system consists of generation and consumption distributed in the grid. Thus inertia and frequency control is distributed and connected through the grid. In this project, the modelling of the power system and the FCR providing units is performed using one machine equivalent; assumptions for this are given below.

Studies are performed using one machine equivalents for the sake of simplicity. For the same reason and to enable efficient use of linear analysis, power system components like power lines, transformers etc. are omitted. Furthermore, voltage dynamics are also omitted (automatic voltage regulators on generators, load voltage characteristics etc.).

## 3.1 POWER SYSTEM MODEL

The swing equation relates the rotor dynamics with mechanical and electrical power of a single generator as

$$\frac{H_x}{\pi f_0}\frac{d^2\theta_x}{dt^2} = P_{\mathrm{m}x} - P_{\mathrm{e}x} \tag{3.1}$$

where $\theta_x$ is the angle in rad of generator *x*, $H_x$ is the inertia constant, $P_{\mathrm{m}x}$ and $P_{ex}$ are the mechanical and electrical power, respectively, expressed on a power base. Consider synchronous machines on a common system base ($S_\mathrm{n}$). Assume the machine rotors swing coherently, all $d\theta_x/dt$ are equal, we can then add the power and dynamics as

$$\sum_x \frac{H_x}{\pi f_0}\frac{d^2\theta_x}{dt^2} = \sum_x (P_{\mathrm{m}x} - P_{\mathrm{e}x}) \tag{3.2}$$

This results in

$$\frac{H}{\pi f_0}\frac{d^2\theta}{dt^2} = P_\mathrm{m} - P_\mathrm{e} \tag{3.3}$$

where the equivalent inertia constant *H* is given by

$$H = \sum H_x \quad \forall x \tag{3.4}$$

where $H_x$ is the inertia constant of generator *x* on this common power base.

Loads are here modelled not to depend on voltage; therefore, they can be lumped. The static loads are assumed to be frequency dependent in proportion to the frequency deviation.

A linear one mass model together with load frequency dependency then relates the transfer function from power change to frequency change as

$$\Delta f = \frac{f_0}{S_{\mathrm{n}}(2Hs + kf_0)}\Delta P = G(s)\Delta P \tag{3.5}$$

where parameters are specified in Table 1. Thus, this transfer function is a single-input-single-output (SISO) model of the power system.

**TABLE 1: POWER SYSTEM MODEL PARAMETERS**

| Parameter | Value | Description |
|---|---|---|
| $f_0$ | 50 Hz | Nominal frequency |
| $S_{\mathrm{n}}$ | 23 GVA | Rated apparent power of the system |
| $H$ | 120 GWs/23 GW | Inertia constant of the system |
| $k$ | 0.5 (%/Hz of $S_{\mathrm{n}}$) | Load frequency dependency |

The parameter values are set by the framework defined for the work outlined in this report [5]. One shall note that FCR-D can be dimensioned for different system set-ups with corresponding system parameters. The system set-up affects the values coming out from the FCR-D requirement development process.

## 3.2 HYDRO UNIT MODEL

The hydro unit model consists of a PID-type turbine governor with gate droop, gate servo and the hydraulic system (penstock and turbine), as illustrated in Figure 3.

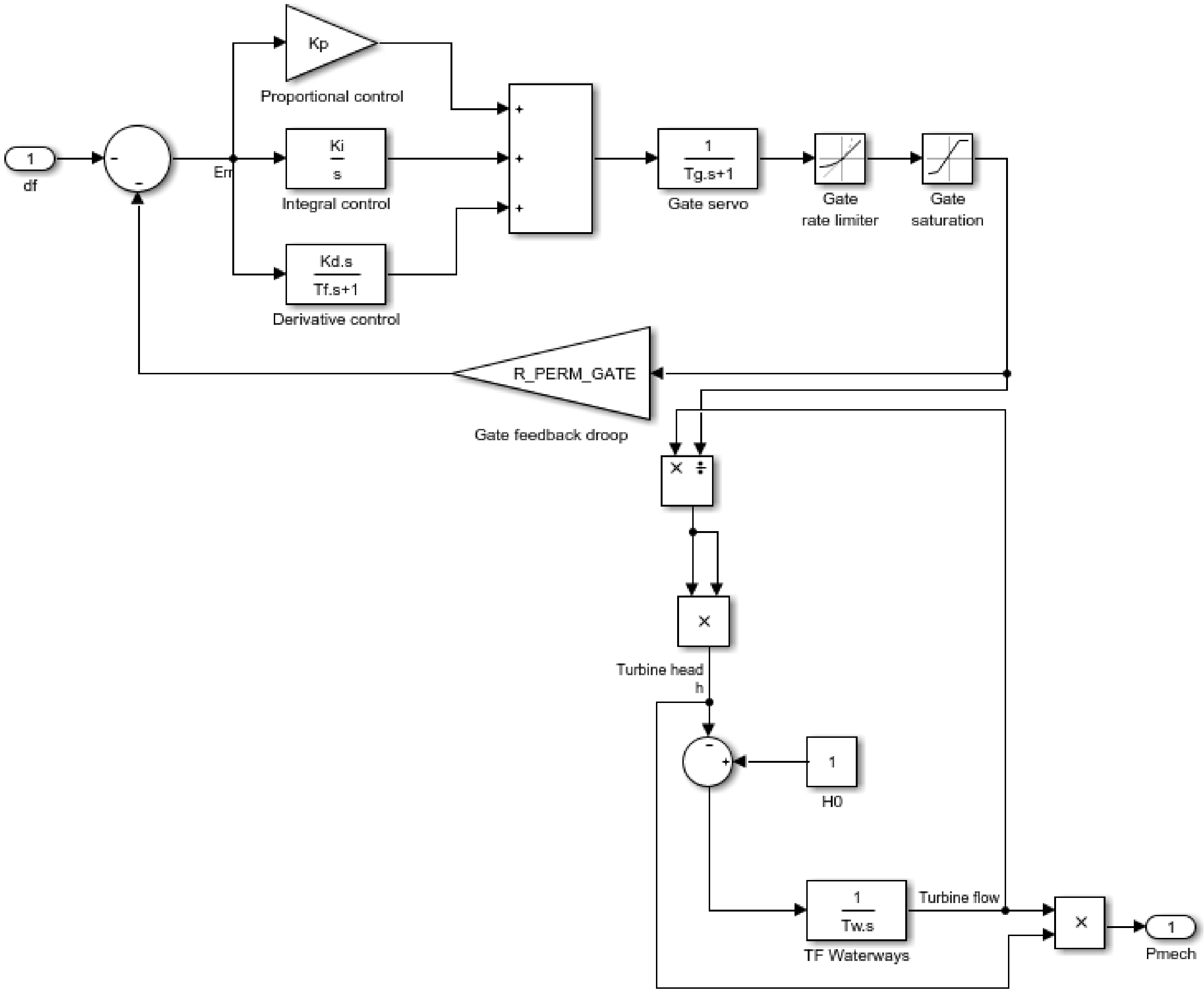

**FIGURE 3: BLOCK DIAGRAM REPRESENTATION OF THE HYDRO UNIT MODEL**

The PID governor has a parallel structure with proportional, integral and derivate control blocks. The derivate control block is equipped with a filter, which is used to reduce measurement noise. The gate servo model includes ramp rate limits for the servo and servo saturation. Penstock is represented using an inelastic water column model and the turbine is represented using a generic turbine model [6, p. 55]. Together these form a non-linear representation of the hydraulic system. Fixed parameters used are listed in Table 2. The parameters used are based on feedback received from hydro power producers and experts working in the field and can be considered as typical values for a large population of the existing units.

TABLE 2: HYDRO UNIT PARAMETERS

| Parameter | Value | Description |
|---|---|---|
| $T_\mathrm{f}$ | 0.15 (s) | Filter time constant for derivate part |
| $T_\mathrm{g}$ | 0.2 (s) | Gate servo time constant |
| $R_\mathrm{open}$ | 0.1 (pu/s) | Gate servo ramp-rate limit for opening |
| $R_\mathrm{close}$ | -0.1 (pu/s) | Gate servo ramp-rate limit for closing |
| $G_\mathrm{max}$ | 1.0 (pu) | Gate saturation upper limit |
| $G_\mathrm{min}$ | 0.0 (pu) | Gate saturation lower limit |

The above described model is used for time domain simulations. For linear analysis (stability analysis) the model is linearised. Linearisation is performed by removing the gate ramp-rate limiters, gate saturation and linearising the waterways. For linear representation of the waterways the following transfer function is used

$$\frac{-Y_0\, T_\mathrm{W}\, s\ +\ 1}{\frac{T_w}{2}\, Y_0\, s\ +\ 1} \tag{3.6}$$

where,
$Y_0$ is the loading of the unit (pu)
$T_\mathrm{w}$ is the water time constant (s).

The hydro unit model described is very general which means that it is not well suited for in-detail simulations of specific hydro units. On the other hand, the model captures general dynamics of different turbine types. The model does not include, for example, servo positioning loops, dynamics of double regulated turbines (Kaplan turbines), turbine self-regulation etc.

# 4. DESIGN OF REQUIREMENTS

The scope of the requirement design was to develop specific requirements based on both performance and stability that fulfils system's needs. Requirements have been designed with the goal of not to disqualify any units due to performance but instead scale the capacity delivered by a unit. If a unit delivers according to reference performance, the unit will get the full activation steady state power as its capacity. If a unit delivers below reference performance, the capacity will be reduced in relation to the actual performance. The stability requirement on the other hand is a strict requirement that must be fulfilled in order to be qualified for providing the service. In this way, more units will be able to enter the market even if their capacity is reduced. These requirements aim to ensure that the system needs are met.

## 4.1 DEVELOPMENT OF THE REQUIREMENTS

The fundamental idea behind the requirement design is to map the needs of the power system into specific, locally testable, requirements on individual units. Figure 4 shows the procedure of the development of the requirements as a flow chart.

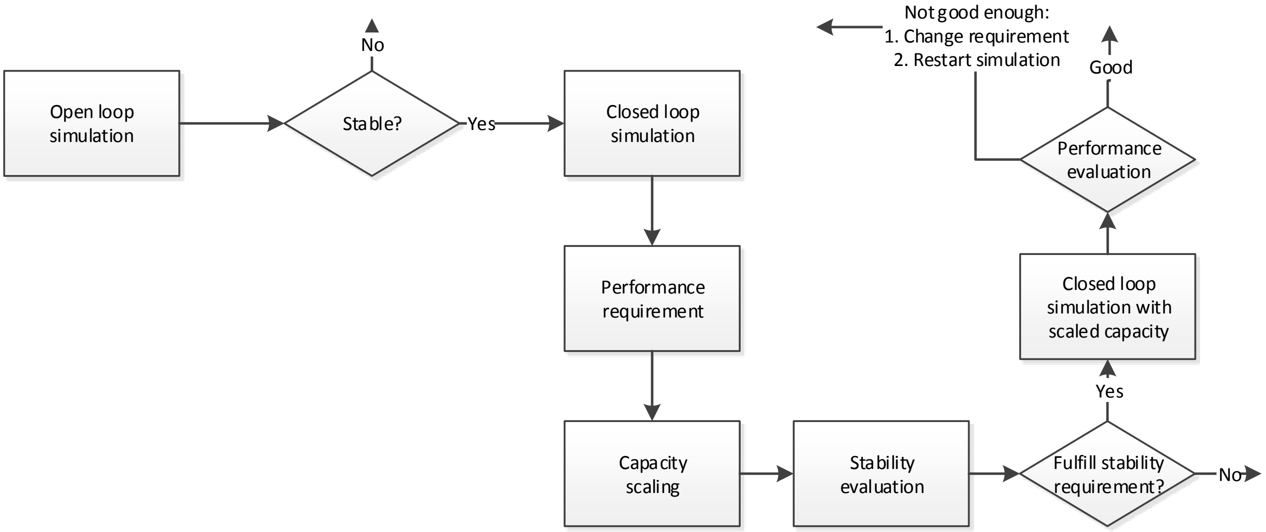

FIGURE 4: FLOW CHART OF THE DEVELOPMENT PROCEDURE OF THE REQUIREMENTS

Open loop simulations have been performed for a great number of parameter sets, where turbine governor parameters (PID gains and droop) and hydro power unit parameters (water time constant and loading) were varied. In this way the expected parameter variation in the existing units are covered. Ranges of the simulated parameter variations are presented in Table 3.

TABLE 3: SIMULATED PARAMETER VARIATIONS

| Parameter | Range |
|---|---|
| $K_\mathrm{p}$ | 2 – 15 [pu] |
| $K_\mathrm{i}$ | 0.05 – 5 [pu] |
| $K_\mathrm{d}$ | 0 – 10 [pu] |
| $droop$ | 2 – 12 [%] |
| $T_\mathrm{w}$ | 1.2 - 1.8 [s] |
| $Loading$ | 40 – 80 [%] |

In total there are 999 600 simulated parameter sets (configurations with so high initial loading and low droop that it is not possible to activate FCR-D fully were filtered out). FCR-D capacity (procured amount of the service) is set to 1450 MW.

After open loop simulations, all stable parameter sets are simulated in closed loop for a major disturbance in form of a very fast and large power imbalance (instantaneous loss of 1450 MW of generation). The FCR-D capacity for each unit in this simulation is based on the steady state delivery at full activation frequency, 49.5 Hz with activation starting at 49.9 Hz.

Open and closed loop responses are compared for the same parameter sets in order to identify performance requirement in open loop response that in the best way represent the desired closed loop performance. The two most important properties of the requirements are to qualify units with good performance and disqualify units with bad performance. It is, however, impossible to find a perfect requirement without any overlap of these two properties. There is a trade-off between system performance, disqualifying good units and qualifying bad units.

Based on the open loop response and reference performance set by the requirement, new scaled unit capacity is obtained. After the new scaled capacity is calculated, the unit stability is evaluated using the stability requirement. The stability requirement is the stability margin (maximum sensitivity of 2.31) explained in Section 4.7.

Units fulfilling the stability requirement are simulated in closed loop again with the new scaled unit capacity to ensure desired system performance is achieved.

## 4.2 OPEN LOOP SIMULATION

The open loop simulations are performed with a pre-determined input frequency instead of the frequency from the power system (closed loop). In this way, the output of the unit will not affect the input frequency signal. The input reference frequency signal can use any shape and amplitude. Two common ways are to either use a step or a ramp for testing the open loop response.

One benefit of using a ramp is the correspondence with the initial frequency fall in the real power system. In Figure 5 the frequency measurement from an actual disturbance is shown in blue. As shown by the red line, the frequency fall can be approximated very well using a ramp.

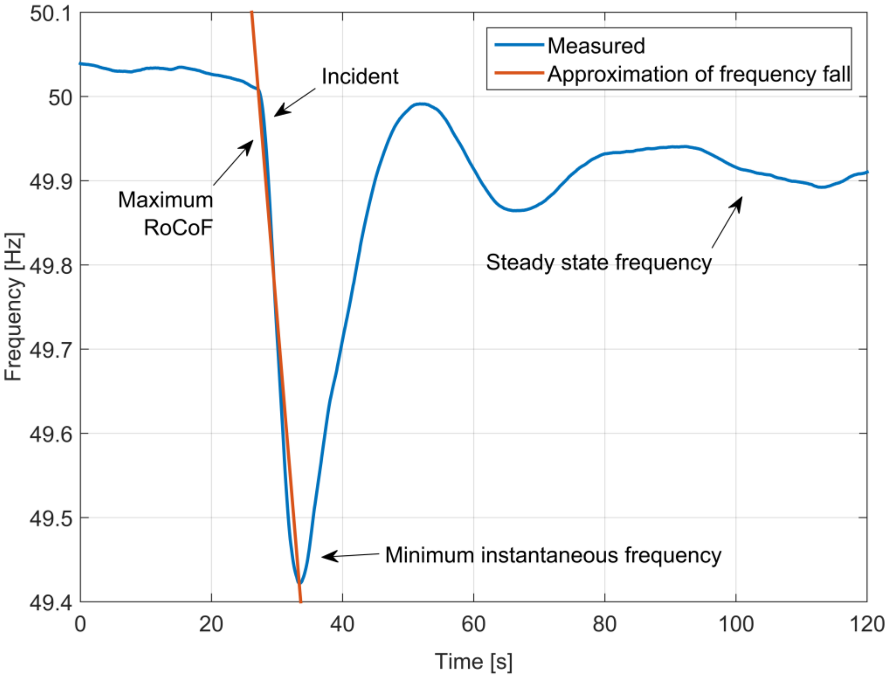

**FIGURE 5: THE FREQUENCY FALL APPROXIMATED BY A RAMP**

Lower power system kinetic energy results in steeper slope of the ramp. A frequency input in form of a step is in that sense considered as an extremely fast change of the frequency which corresponds to unrealistically low kinetic energy. The highest absolute RoCoF that will occur during a disturbance in the system with kinetic energy of 120 GWs (dimensioning value) can be calculated as

$$\frac{df}{dt} = \frac{\Delta P_{\text{disturbance}} \cdot f_0}{2 \cdot E_{\text{kin}}} = \frac{1450 \cdot 50}{2 \cdot 120000} \approx -0.3\ [Hz/s] \tag{4.1}$$

where $\Delta P_{\text{disturbance}}$ is the dimensioning disturbance and $E_{\text{kin}}$ is the dimensioning system kinetic energy.

With a disturbance of 1450 MW and a kinetic energy of 120 GWs the resulting RoCoF is -0.3 Hz/s. In the closed loop power system the absolute RoCoF starts to reduce as the power imbalance is reduced by frequency dependent loads and activation of reserves. The power imbalance is, however, reduced differently depending on other reasons like the type and amount of machines delivering the reserves. Hence, it is impossible to beforehand know the RoCoF over time for a typical disturbance.

Another property of the open loop test signal is the amplitude. In the framework the activation start level (49.9 Hz), full activation level (49.5 Hz) and the minimum allowed instantaneous frequency (49.0 Hz) are specified.

One benefit with using a ramp instead of a step is the more realistic response from the turbine governor derivative part in the open loop test.

Based on this, four reasonable alternatives of open loop signals have been analysed:

1. Ramp of -0.3 Hz/s from 49.9 Hz to 49.5 Hz
2. Step from 49.9 Hz to 49.5 Hz
3. Ramp of -0.3 Hz/s from 49.9 Hz to 49.0 Hz
4. Step from 49.9 Hz to 49.0 Hz

Figure 6 shows alternative 3. This signal results in a 3 second long ramp before 49.0 Hz is reached.

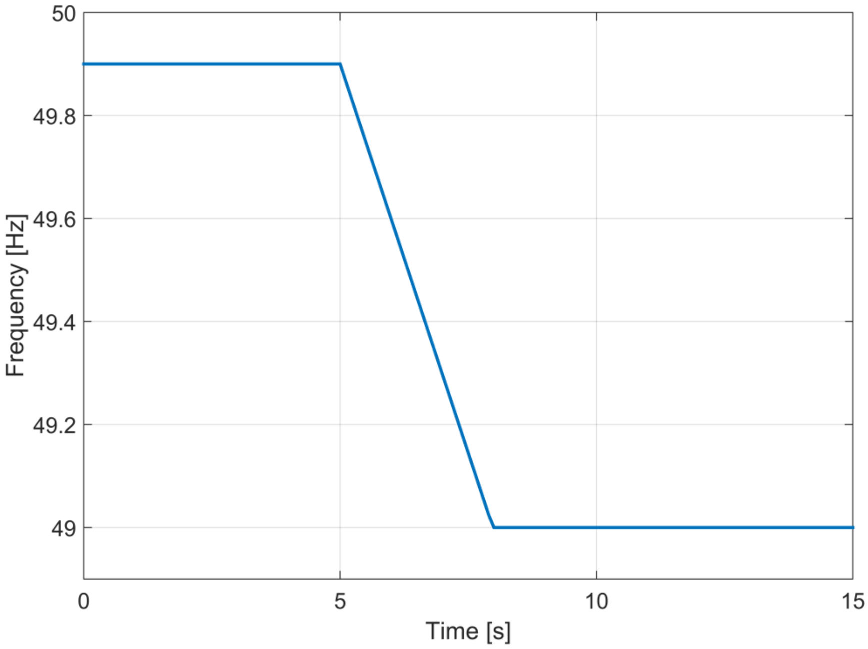

**FIGURE 6: EXAMPLE OF AN OPEN LOOP FREQUENCY INPUT SIGNAL**

In Figure 7 examples of five open loop power responses are shown in per unit for the input signal in Figure 6. 1 pu is defined as the steady state power at full activation frequency 49.5 Hz. The power is integrated and shown as energy in Figure 8.

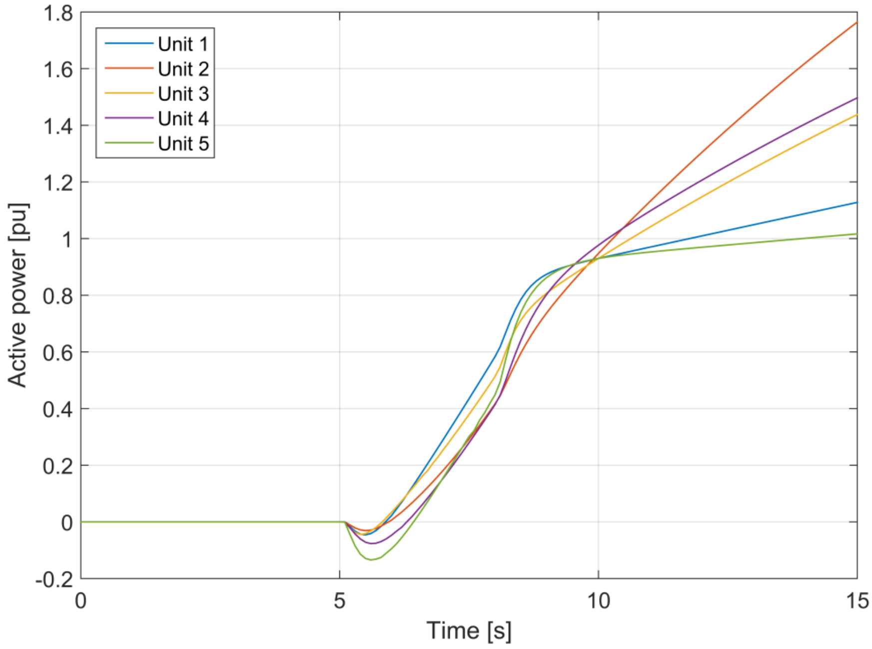

**FIGURE 7: EXAMPLE OF SIMULATED OPEN LOOP RESPONSE – POWER**

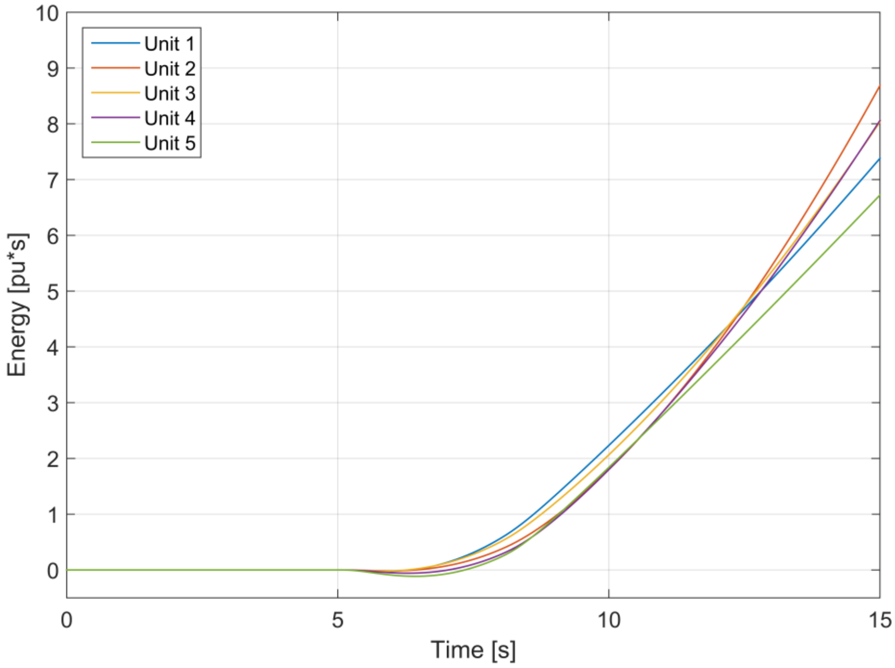

**FIGURE 8: EXAMPLE OF SIMULATED OPEN LOOP RESPONSE – ENERGY**

The steady state power is defined as the activation at 49.5 Hz. If a test signal goes below this value and the loading level of the unit allows, the result will be a power above 1 pu. This is, however, not required for the units.

By comparing the figures it can be seen that a large non minimum phase response (the initial active power decrease) results in initially lower energy which is not beneficial for the power system performance.

## 4.3 CLOSED LOOP SIMULATION

After open loop simulations, the parameter sets are simulated in closed loop subjected to a major disturbance of 1450 MW generation disconnection. The frequency at the time of the disturbance is set to the same as for open loop, 49.9 Hz. The amount of FCR-D is 1450 MW, where the capacity is defined as the steady state power at 49.5 Hz.

In Figure 9 the minimum instantaneous frequency for every stable parameter combination is shown. Parameter sets meeting the performance constraint with a minimum frequency above 49.0 Hz are marked in green and parameter sets not meeting the performance constraint are marked in red. Table 4 shows the two most important results from the closed loop simulations. Here, a smaller amount of different parameter sets were simulated (168 300 instead of 999 600; $K_\mathrm{p}$ upper limit was set to 10 pu, $K_\mathrm{i}$ lower limit was set to 0.1 pu and $K_\mathrm{d}$ upper limit was set to 1 pu).

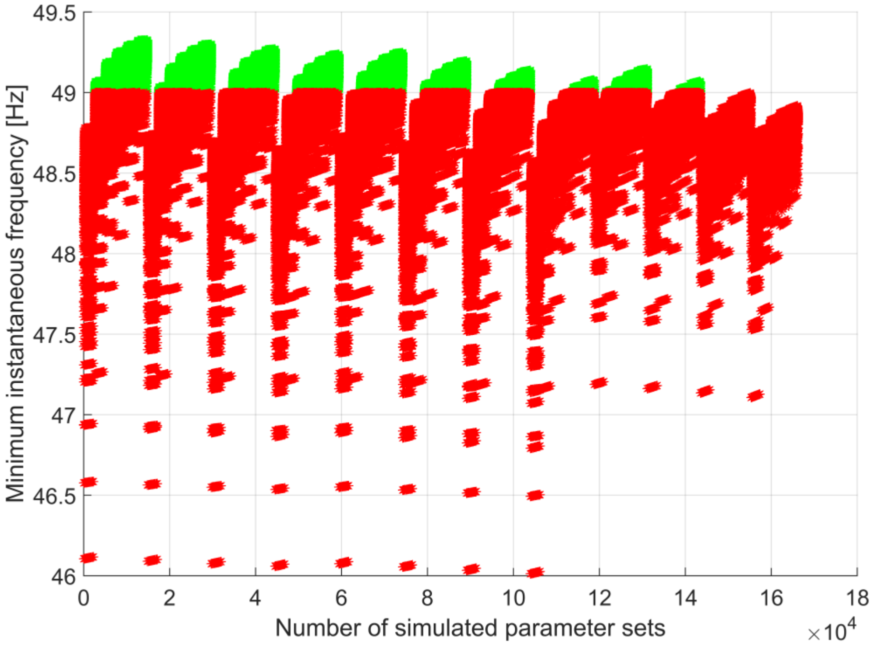

FIGURE 9: MINIMUM INSTANTANEOUS FREQUENCY IN CLOSED LOOP SIMULATIONS FOR A DISTURBANCE OF 1450 MW

TABLE 4: RESULTS FROM CLOSED LOOP SIMULATIONS

| Result | Value |
|---|---|
| Unstable parameter sets | 2 020 |
| Parameter sets under 49.0 Hz of all stable parameter sets | 67.73 % |

The results of the closed loop simulation clearly indicate that it is only a limited share of the parameter sets that fulfil the performance constraint of 49.0 Hz. To ensure that the desired system performance is reached, individual units must be evaluated against both the requirements for performance and stability.

## 4.4 OPEN LOOP TEST SIGNAL

The four open loop test signal alternatives presented in Section 4.2 have been analysed to select the open loop signal that provides a response mapped to the closed loop performance in the best way. In the open loop test, it is possible to set up requirements for either delivered power, energy or the combination of these. The evaluation between performance of open loop signals is done in a way where a requirement is set up at a specific time for the lowest of all open loop responses with a frequency over 49.0 Hz in the closed loop simulations. All open loop responses below this value will then result in a frequency below 49.0 Hz and in this evaluation it is considered to be disqualified. In this way, no parameter sets with a frequency above 49.0 Hz will be disqualified. The open loop evaluation will be based on the share of parameter sets with responses above the requirement but still result in a frequency below 49.0 Hz in the closed loop. The results are shown in Table 5. A lower value is better, 0 % represents that no parameter set with a frequency below 49.0 Hz are qualified and at the same time all qualified sets keep the frequency above 49.0 Hz, a perfect requirement. The specific time of the requirement is optimized for each requirement type to provide as low value as possible. For double requirements, two times are used.

Five alternatives of requirements are analysed:

1. Power requirement at time t1
2. Energy requirement at time t1
3. Power requirement at time t1 and power requirement at time t2
4. Power requirement at time t1 and energy requirement at time t2
5. Energy requirement at time t1 and energy requirement at time t2

The small difference between Table 5 and Table 4 regarding the share of parameter sets under 49.0 Hz (66.3 and 67.7 %) is explained by the way of performing the simulations. When the first open loop simulations were performed, a stability requirement was defined by the gain and phase margin, resulting in slightly different values (later on, this was changed to stability margin).

**TABLE 5: EVALUATION BETWEEN DIFFERENT OPEN LOOP SIGNALS**

| **Result** | **Ramp** | | **Step** | |
|---|---|---|---|---|
| Open loop | 49.9-49.5 Hz | 49.9-49.0 Hz | 49.9-49.5 Hz | 49.9-49.0 Hz |
| Parameter sets under 49.0 Hz of all stable parameter sets [%] | 66.3 | 66.3 | 66.3 | 66.3 |
| Power [%] | 19.1 | 6.9 | 17.8 | 19.3 |
| Energy [%] | 6.4 | 5.8 | 12.1 | 22.8 |
| Power & Power [%] | 12.5 | 3.4 | 11.4 | 14.6 |
| Power & Energy [%] | 5.3 | 3.2 | 7.9 | 14.0 |
| Energy & Energy [%] | 4.0 | 4.2 | 9.1 | 20.4 |

From the table it is clear that the open loop ramp from 49.9 to 49.0 Hz has the lowest value and thereby the best correspondence between the open loop response and closed loop performance. Therefore, this is decided to be used as the open loop test signal.

**Main point:** Open loop frequency test signal will be a ramp from 49.9 to 49.0 Hz with a RoCoF of -0.3 Hz.

## 4.5 PERFORMANCE REQUIREMENT

The performance requirement is designed so that all units shall be able to provide the service but with a capacity that is in relation to their actual contribution from the system point of view. The requirements are stated as goals in the open loop response in order to ensure a good closed loop performance when the system is exposed to a major disturbance.

In addition to the type of requirement (five different alternatives listed in Section 4.4), the times and levels must be selected. This result in a multi-dimensional optimisation to ensure good performance and at the same time to not to penalise units that deliver good performance. Three Key Performance Indicators (KPIs) were set-up in order to evaluate different requirements:

- KPI 1: The share of units that qualify according to the requirement and keep $f_{\min} > 49.0$ Hz of all units keeping $f_{\min} > 49.0$ Hz [%]
- KPI 2: The share of units that qualify according to the requirement and do not keep $f_{\min} > 49.0$ Hz of all units not keeping $f_{\min} > 49.0$ Hz [%]
- KPI 3: KPI 1 and KPI 2 combined, that is KPI3 = 100 – KPI1 + KPI2

KPI 1 indicates how well the requirement is qualifying good performance, the higher value the better. KPI 2 indicates how good the requirement is at qualifying bad performance, the lower value the better. KPI 3 is a combination of KPI 1 and KPI 2, the lower value the better. The KPIs have been calculated by varying both the time and the level of the requirements. The time for requirement on power and energy was varied from 3 seconds to 10 seconds in steps of 0.5 seconds. The level of requirement for power was varied from 0 pu to 1.0 pu in steps of 0.01 pu and from 0 pu·s to 10 pu·s in steps of 0.1 pu·s for energy. The time is defined from the start of the open loop ramp.

The KPI optimisation does not capture the need for ensuring power balance at 49.0 Hz in the requirements. At 49.0 Hz power balance must be restored, otherwise the frequency will continue to decrease. At 49.0 Hz load has reduced by 103.5 MW from 49.9 Hz due to the frequency dependent load, using the specified model parameters. That means that the rest of the power imbalance must be balanced by FCR-D, otherwise the minimum instantaneous frequency will decrease below 49.0 Hz. The required power from FRC-D is calculated as

$$P_{\text{req}} = \frac{\Delta P_{\text{disturbance}} - \Delta P_{\text{load}}}{\Delta P_{\text{disturbance}}} = \frac{1450 - 23000 \cdot 0.9 \cdot 0.005}{1450} \approx 0.93\ [\text{pu}^5] \qquad (4.2)$$

Without this requirement, it is not possible to ensure that the power system gets the needed FCR-D activation.

Table 6, Table 7, Table 8, Table 9 and Table 10 show some of the results from the optimisation. The tables are colour mapped from green (good) to red (bad) and sorted based on KPI 3. Table 10 is filtered so that both requirements for power and energy are specified for the same time. All power requirements are also filtered to have power requirement of at least 0.93 pu.

**TABLE 6: KPIS FOR POWER REQUIREMENT AT DIFFERENT VALUES AND TIMES**

| t1 (s) | Power (pu) | KPI 1 (%) | KPI 2 (%) | KPI 3 |
|---|---|---|---|---|
| 4,5 | 0,94 | 91,6 | 4,8 | 13,2 |
| 4,5 | 0,95 | 90,2 | 4,2 | 14,0 |

**TABLE 7: KPIS FOR ENERGY REQUIREMENT AT DIFFERENT VALUES AND TIMES**

| t1 (s) | Energy (pu·s) | KPI 1 (%) | KPI 2 (%) | KPI 3 |
|---|---|---|---|---|
| 6,5 | 3,5 | 96,8 | 2,5 | 5,8 |
| 7 | 4 | 97,8 | 4,0 | 6,2 |
| 6 | 2,9 | 98,3 | 4,7 | 6,4 |
| 7 | 4,1 | 95,5 | 2,1 | 6,7 |
| 6 | 3 | 95,1 | 2,3 | 7,2 |
| 7,5 | 4,6 | 96,8 | 4,0 | 7,2 |

**TABLE 8: KPIS FOR DOUBLE POWER REQUIREMENT AT DIFFERENT VALUES AND TIMES**

| t1 (s) | Power 1 (pu) | t2 (s) | Power 2 (pu) | KPI 1 (%) | KPI 2 (%) | KPI 3 |
|---|---|---|---|---|---|---|
| 3,5 | 0,72 | 6 | 0,93 | 96,7 | 2,5 | 5,8 |
| 3,5 | 0,72 | 6 | 0,94 | 96,4 | 2,3 | 5,9 |
| 3,5 | 0,71 | 6 | 0,93 | 97,4 | 3,4 | 6,0 |
| 3,5 | 0,73 | 6 | 0,93 | 95,8 | 1,8 | 6,0 |
| 3,5 | 0,72 | 5,5 | 0,93 | 95,7 | 1,8 | 6,1 |

---

[5] 1 pu on system level represents to the total amount of FCR-D of 1450 MW. This is mapped to the capacity of the individual units.

TABLE 9: KPIS FOR DOUBLE ENERGY REQUIREMENT AT DIFFERENT VALUES AND TIMES

| t1 (s) | Energy 1 (pu·s) | t2 (s) | Energy 2 (pu·s) | KPI 1 (%) | KPI 2 (%) | KPI 3 |
|---|---|---|---|---|---|---|
| 6 | 2,9 | 8,5 | 5,5 | 97,9 | 1,9 | 4,0 |
| 6 | 2,9 | 9 | 6 | 97,9 | 2,0 | 4,1 |
| 6 | 2,9 | 8 | 5 | 97,8 | 1,9 | 4,1 |
| 6 | 2,9 | 9,5 | 6,5 | 98,0 | 2,1 | 4,1 |
| 6 | 2,9 | 9,5 | 6,6 | 97,6 | 1,8 | 4,2 |

TABLE 10: KPIS FOR POWER AND ENERGY REQUIREMENT AT DIFFERENT VALUES AND TIMES

| t1 (s) | Power 1 (pu) | t2 (s) | Energy 2 (pu·s) | KPI 1 (%) | KPI 2 (%) | KPI 3 |
|---|---|---|---|---|---|---|
| 6 | 0,93 | 6 | 2,9 | 97,2 | 1,3 | 4,1 |
| 6 | 0,94 | 6 | 2,9 | 96,9 | 1,3 | 4,3 |
| 5,5 | 0,93 | 5,5 | 2,3 | 97,5 | 2,1 | 4,6 |
| 6 | 0,95 | 6 | 2,9 | 96,5 | 1,2 | 4,7 |
| 6,5 | 0,93 | 6,5 | 3,5 | 96,3 | 1,3 | 5,0 |
| 5,5 | 0,94 | 5,5 | 2,3 | 96,9 | 1,9 | 5,0 |
| 5,5 | 0,93 | 5,5 | 2,4 | 95,2 | 0,3 | 5,0 |
| 6 | 0,96 | 6 | 2,9 | 96,1 | 1,2 | 5,1 |
| 6,5 | 0,94 | 6,5 | 3,4 | 98,1 | 3,2 | 5,2 |
| 6,5 | 0,94 | 6,5 | 3,5 | 96,1 | 1,2 | 5,2 |
| 6,5 | 0,95 | 6,5 | 3,4 | 97,8 | 3,2 | 5,4 |
| 6,5 | 0,95 | 6,5 | 3,5 | 95,9 | 1,2 | 5,4 |
| 5 | 0,93 | 5 | 1,8 | 95,2 | 0,6 | 5,4 |
| 5,5 | 0,95 | 5,5 | 2,3 | 96,3 | 1,8 | 5,4 |
| 6 | 0,97 | 6 | 2,9 | 95,6 | 1,1 | 5,5 |

The tables clearly indicate that it is preferred to use two requirements. Since with lower kinetic energy the time of the minimum frequency will occur earlier compared to today, the project has decided to specify a requirement time as early as possible to ensure power balance at that time. This is important considering other non-linarites not included in the simulation model. In Table 10 the 15 best requirement combinations are listed for power and energy. Of these combinations the shortest requirement time is 5 s, power = 0.93 pu and energy = 1.8 pu·s. The good thing with this combination is the low KPI 2, indicating that few good parameter sets are punished with scaled capacity.

For full KPI tables, see Appendix 1.

**Main point:** The performance requirement (reference performance) is decided to:

$$P_{\mathrm{ref}}(5\ \mathrm{s}) = 0.93\ [\mathrm{pu}]$$

$$E_{\mathrm{ref}}(5\ \mathrm{s}) = 1.8\ [\mathrm{pu} \cdot \mathrm{s}]$$

## 4.6 CAPACITY SCALING

The reimbursement is based on a pay for performance principle. If a unit delivers according to the reference performance, the unit will be reimbursed for the full steady state power. Because the unit delivers according to the system needs, the unit capacity is not scaled.

If a unit delivers below the reference performance, the unit capacity will be reduced. Capacity reduction will be done based on the relation between the reference performance and the measured values. The FCR-D capacity is calculated as

$$C_{\mathrm{FCR-D}} = \min\left(\frac{P(5\ \mathrm{s})}{P_{\mathrm{ref}}(5\ \mathrm{s})}, \frac{E(5\ \mathrm{s})}{E_{\mathrm{ref}}(5\ \mathrm{s})}, 1\right) \cdot \Delta P_{\mathrm{ss}}\ [\mathrm{MW}] \tag{4.3}$$

where $C_{\mathrm{FCR-D}}$ is the unit capacity after scaling. $P(5\ \mathrm{s})$ and $E(5\ \mathrm{s})$ are the measured power (pu) and energy (pu·s) at five seconds after the start of the open loop ramp, respectively. $\Delta P_{\mathrm{ss}}$ is the steady state power at full activation frequency (49.5 Hz).

## 4.7 STABILITY REQUIREMENT

In order to ensure stable frequency control in the power system a stability requirement is designed. The requirement for stability is based on the maximum allowed sensitivity of the closed loop system. The requirement is transferred and analysed in a Nyquist diagram. A value of 2.31 is used as the required maximum sensitivity (based on a phase margin of 25 degrees)

$$M_s = \frac{1}{2 \cdot \sin\left(\frac{\delta_{\mathrm{m}}}{2} \cdot \frac{\pi}{180}\right)} = \frac{1}{2 \cdot \sin\left(\frac{25}{2} \cdot \frac{\pi}{180}\right)} \approx 2.31 \tag{4.4}$$

In the Nyquist plot the stability margin is shown as a circle in the complex plane with a radius $r$ and centre in the (-1, 0) point. To take measurement uncertainties into account, a 95 % scaling factor is included in the requirement. The reason for the scaling factor is to not disqualify units if they are just on the wrong side of the requirement due to poor measurement quality.

$$r = \frac{1}{M_s} \cdot 0.95 \approx 0.41 \tag{4.5}$$

The stability requirement is a strict requirement the units have to fulfil in order to qualify for the delivery of the service. To qualify, the unit´s response including capacity scaling must lie outside the stability margin circle without encircling the (-1, 0) point.

In the simulation, the unit transfer function from input frequency deviation to the output power is analysed in a linearized model. See example of two unit responses using the Bode diagram in Figure 10.

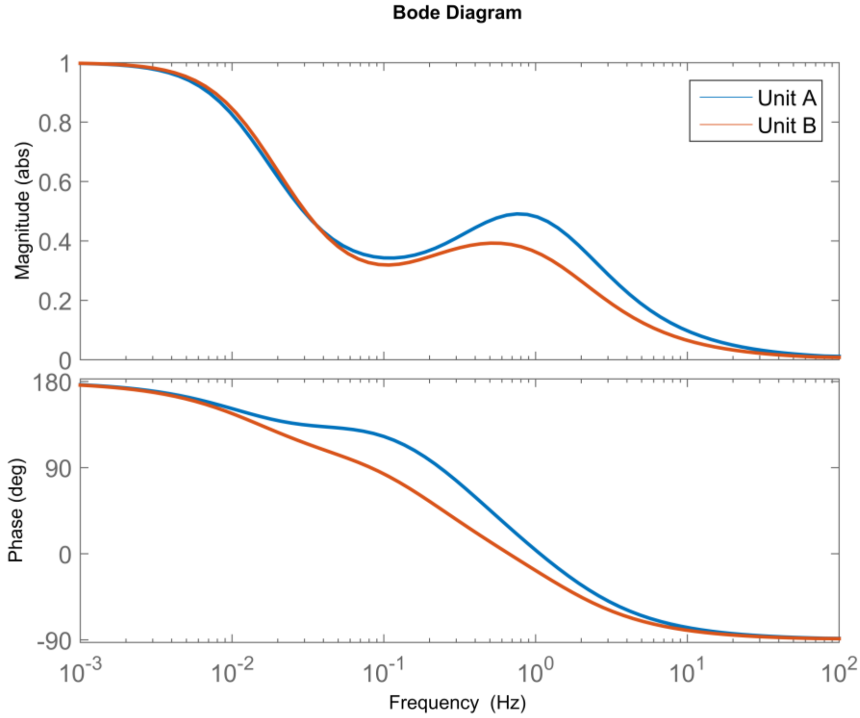

FIGURE 10: BODE DIAGRAM OF TWO NORMALIZED TRANSFER FUNCTIONS FROM FREQUENCY DEVIATION TO POWER

In order to obtain the Nyquist curve, the normalized unit transfer function $FCR_{\text{unit}}$ is multiplied with the scaled grid transfer function

$$L(j\omega) = FCR_{\text{unit}} \cdot \left[-\frac{\Delta P_{\text{ss}}}{C_{\text{FCR-D}}} \cdot \frac{\Delta P_{\text{disturbance}}}{0.4\ \text{Hz}} \cdot \frac{f_0}{S_n} \cdot \frac{1}{2Hs + k \cdot f_0}\right] \tag{4.6}$$

The term $\frac{\Delta P_{\text{ss}}}{C_{\text{FCR-D}}}$ represents the scaling of capacity due to the performance requirement. This term is needed to ensure stability for the actual regulation strength of the system, as unit FCR capacity can be lower than the steady state power (will lead to higher system regulating strength).

Stability of the units is then evaluated in a Nyquist diagram, an example in shown in Figure 11.

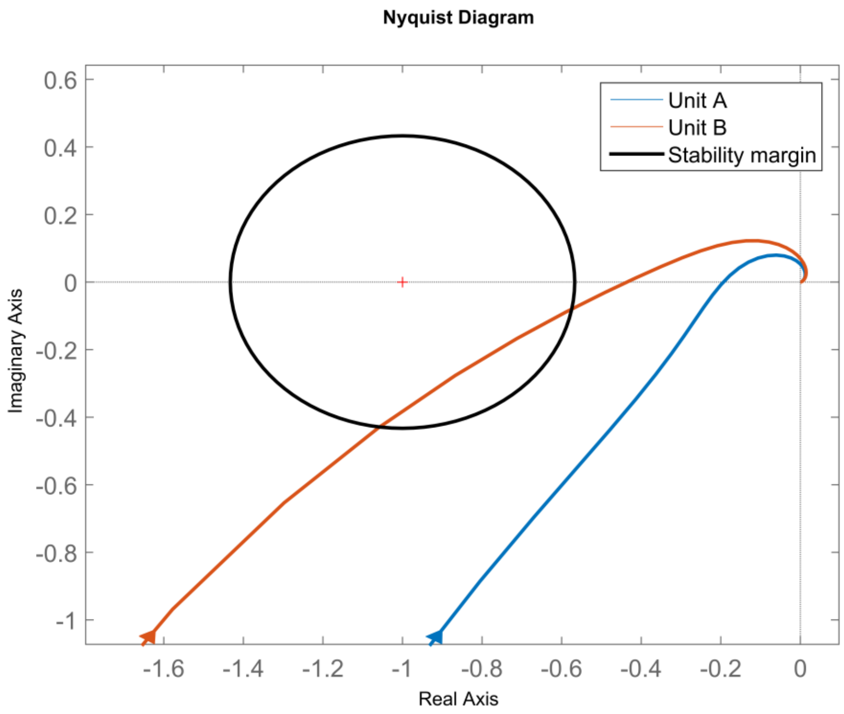

**Figure 11: Stability is evaluated in a Nyquist diagram**

From the Nyquist diagram it is clear that Unit B is disqualified due to stability because the Nyquist curve enters the stability margin circle.

The 166 280 stable parameter sets (Section 4.3) were scaled according to the performance requirement and evaluated for the stability requirement. The result is shown in Table 11.

**Table 11: Stability evaluation of simulated and scaled parameter sets**

| Result | Value |
|---|---|
| Parameter sets disqualified for stability | 74 426 |

In total there are only approximately 55 % of the parameter sets that qualifies for stability. The reason for this is that the units have problems to deliver the reference performance and thereby to meet the system needs. If a unit only achieves a very low capacity, the scaling ratio $\frac{\Delta P_{\mathrm{ss}}}{C_{\mathrm{FCR-D}}}$ will be very high and make it harder to fulfill the stability requirement. Table 12 shows the share of qualified parameter sets according to the droop, loading and water time constant.

**TABLE 12: SHARE OF PARAMETER SETS QUALIFYING FOR STABILITY BASED ON DROOP, LOADING AND WATER TIME CONSTANT**

| Droop 2 % | | | | | Droop 8 % | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Loading [%] \ Tw [s] | 1.2 | 1.4 | 1.6 | 1.8 | Loading [%] \ Tw [s] | 1.2 | 1.4 | 1.6 | 1.8 |
| 40 | 71 | 65 | 60 | 54 | 40 | 94 | 89 | 85 | 79 |
| 60 | 55 | 45 | 36 | 23 | 60 | 90 | 71 | 57 | 39 |
| 80 | 0 | 0 | 0 | 0 | 80 | 58 | 34 | 1 | 0 |
| Droop 4 % | | | | | Droop 10 % | | | | |
| Loading [%] \ Tw [s] | 1.2 | 1.4 | 1.6 | 1.8 | Loading [%] \ Tw [s] | 1.2 | 1.4 | 1.6 | 1.8 |
| 40 | 82 | 78 | 72 | 66 | 40 | 96 | 92 | 87 | 82 |
| 60 | 68 | 57 | 43 | 28 | 60 | 82 | 73 | 57 | 40 |
| 80 | 45 | 24 | 1 | 0 | 80 | 57 | 35 | 1 | 0 |
| Droop 6 % | | | | | Droop 12 % | | | | |
| Loading [%] \ Tw [s] | 1.2 | 1.4 | 1.6 | 1.8 | Loading [%] \ Tw [s] | 1.2 | 1.4 | 1.6 | 1.8 |
| 40 | 90 | 86 | 81 | 75 | 40 | 97 | 94 | 89 | 84 |
| 60 | 76 | 66 | 53 | 33 | 60 | 84 | 73 | 55 | 38 |
| 80 | 54 | 29 | 1 | 0 | 80 | 55 | 32 | 1 | 0 |

As the table shows, it is difficult to qualify for stability with high water time constant and loading of the unit. Also, it is more difficult to qualify with low droops.

## 4.8 CLOSED LOOP SIMULATION WITH SCALED CAPACITY

To ensure that the desired system performance is achieved, new closed loop simulations are performed using the parameter sets qualified for stability. In the new closed loop simulations the scaled capacity according to the performance requirement is used. The minimum instantaneous frequency is shown in Figure 12 and the results are presented in Table 13.

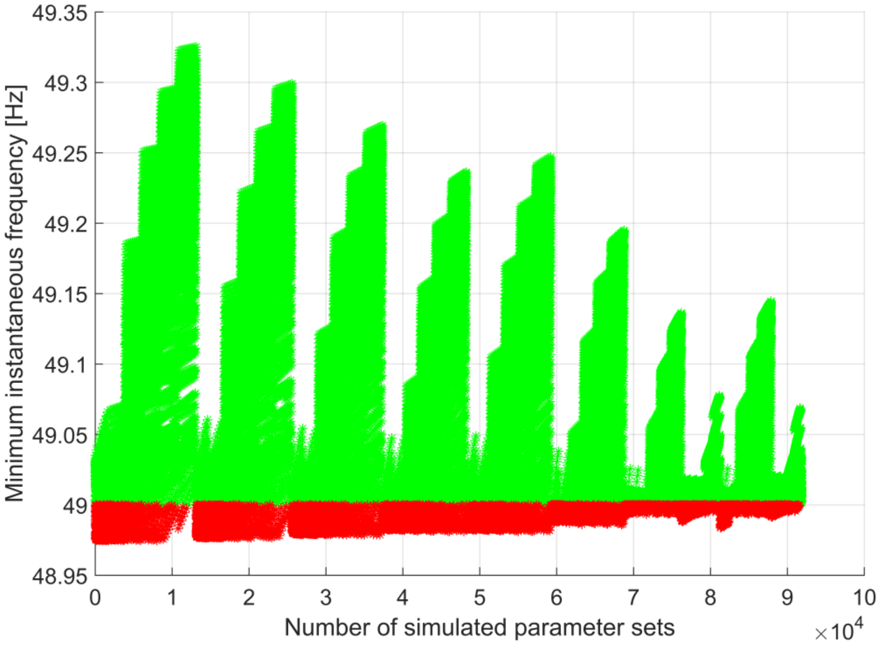

**FIGURE 12: MINIMUM INSTANTANEOUS FREQUENCY IN CLOSED LOOP SIMULATIONS FOR A LOSS OF 1450 MW GENERATION USING THE SCALED CAPACITY AND STABILITY REQUIREMENT**

**TABLE 13: RESULTS FROM CLOSED LOOP SIMULATIONS USING THE SCALED CAPACITY AND STABILITY REQUIREMENT**

| Result | Value |
|---|---|
| Parameter sets under 49.0 Hz of all parameter sets qualifying the stability requirement | 25.20 % |
| Average minimum instantaneous frequency of parameter sets below 49.0 Hz | 48.99 Hz |
| Lowest minimum instantaneous frequency | 48.97 Hz |
| Number of parameter sets qualifying the stability requirement raised from < 49.0 Hz to > 49.0 Hz with capacity scaling | 17 138 |

The simulation results show a great improvement of the system performance compared to Figure 9. In the unscaled closed loop simulations large portion of parameter sets have a frequency below 49.0 Hz, some as low as 46 Hz. After the capacity scaling and evaluation of stability requirement, all parameter sets will have a minimum instantaneous frequency very close to 49.0 Hz. Even though there are parameter sets with a frequency below 49.0 Hz, they are all very close to 49.0 Hz. If no parameter set below 49.0 Hz shall be qualified the requirements must be tougher and the levels set higher. This will also result in a higher share of units with a frequency above 49.0 Hz being disqualified.

# 5. TEST PROCEDURE

This chapter discusses how the unit performance (FCR-D capacity) and compliance with the stability requirement can be tested in practice.

Often faced problem with practical testing is that it is feasible to test only a limited amount of operational conditions due to time and budget limitations. In reality, non-modelled dynamics can affect the behaviour of the tested unit significantly and these dynamics are often non-linear in nature and may only be present during certain operational conditions, both of which make it very difficult to take these into account. Therefore, simplifications are necessary when designing the test procedure.

As outlined *in Technical Requirements for Frequency Containment Reserve Provision in the Nordic Synchronous Area* and *Supporting Document on Technical Requirements for Frequency Containment Reserve Provision in the Nordic Synchronous Area*, on units where setpoint has an effect on the FCR-D response, the requirements shall be tested at minimum and maximum loading where the unit will provide FCR-D. Furthermore, if FCR-D can be provided using multiple droops, tests shall be performed with minimum and maximum droop used (at the minimum and maximum loading).

It is important that testing is performed so that it produces results that can be used as an accurate measure of unit performance during real operation. For instance, the tests shall be performed so that dynamics of all relevant components are captured. For example, the test signal needs to be injected so that the dynamics of the frequency measurement device are observable.

## 5.1 PERFORMANCE

Testing the performance of a unit is rather straightforward as already in the requirement design phase the test signal has been defined. As described earlier in this report, a frequency step from 49.9 Hz to 49.5 and a ramp from 49.9 Hz to 49.0 Hz with a slope of -0.30 Hz/s need to be applied in order to test the performance of an FCR-D providing unit.

Step-response testing of turbine governors is already widely used so there are no new practical issues arising and it is easy to find test equipment suitable for the generation of such signal. Ramp-response testing on the other hand is a lot less common. Therefore, not all currently used test devices can be used to generate the required signal. Especially the required initial offset from the nominal frequency (50.0 Hz) can be a problem for some equipment. However, it is possible to create such signal using rather cheap off-the-shelf function generators.

## 5.2 STABILITY

Testing of the compliance of the stability requirement on the other hand is more complicated. The stability requirement in itself does not at all state what kind of signal shall be used for the testing.

In order to test for stability, the transfer function describing the dynamics of the unit needs to be estimated. This requires an input frequency signal to the turbine governor and measuring the output active power of the unit. However, different types of signals (periodic, aperiodic) with different shapes can be used and then a variety of mathematical methods may be applied to estimate the unit transfer function.

The use of sinusoids as input signal is rather straightforward and can be considered to produce good results. The drawback is that testing using sinusoidal signals is time consuming. Time-wise efficient way would be to use a step-signal but step-signal is not well suited for exciting slow dynamics associated with turbine governing systems, therefore leading to less accurate results. Hence, it was decided to use sinusoids as test signal.

FCR providing units often have non-linear characteristics which means that the amplitude of the test signal needs to be selected with care. When it comes to FCR-D activation, changes in the system are large which means that unit response to small perturbations is of less interest. Therefore, it is justified to use moderately large signal amplitude. It was decided to use 100 mHz as the test signal amplitude, mainly because the same amplitude is used for FCR-N verification. Since the same amplitude is used, it is possible to use FCR-N test data to verify FCR-D stability if FCR-D is provided using the same governor parameters as FCR-N.

Also, it is important to select the time periods to test so that stability can be verified reliably. Due to time limitations, it is possible to only test a limited number of time periods. Time periods of 10, 15, 25, 40, 50 s were selected as they are the short time periods used for FCR-N stability verification. For reliable stability verification, it is not necessary to test with long time periods. However, there is a possibility that other time periods are needed as well (for example, shorter time periods in case of units with very fast dynamics like battery energy storages and HVDC-links).

A large enough number of consecutive periods at a specific time period shall be applied in order to minimise the effect of random process variations. On the other hand, dimensioning of hydraulic systems often enforces limitations on the number of fast consecutive control actions that can be performed. Therefore, it was decided that minimum 5 periods with a stabilized response shall be applied.

## 5.3 DYNAMICS NOT OBSERVABLE DURING TESTING

During testing, the unit must be synchronized to the system. As FCR contribution from one unit is not enough to cause significant changes in the system frequency, the unit is not experiencing speed deviations and therefore typically runs close to nominal speed when being tested. On the other hand, when activating FCR during a large active power disturbance the unit experiences a change in the speed. As units often have speed related dynamics, actual FCR contribution can be affected by the change in the speed. These dynamics are not observable during testing.

On hydro power units discharge and thus the active power is affected by the speed. The impact of the effect, whether it is negative or positive and the size of the impact is dependent on the turbine type. This phenomenon was neglected as the effect was assumed to be negligible due to the fact that on some units this phenomenon contributes positively to system frequency and on some units negatively. Also, the impact of speed deviation on FCR activation cannot be tested in practice.

Furthermore, some units operate with active power feedback instead of gate opening feedback. Then, during real disturbances, the inertial response from the turbine-generator is fed back to the turbine governor via the power feedback loop. This may affect the stability and performance of such unit. As this phenomenon is observable only when speed changes, it cannot be observed during testing. A method for creating a modified open-loop test signal that aims at capturing this effect was developed. However, the method requires that the inertia-constant of the turbine-generator is known and the method assumes specific turbine governor structure. Furthermore, the modified test signal is more difficult to generate compared to the traditional signal. It is not possible to generate the modified test signal using function generators, instead more expensive equipment is needed. Due to these issues, the modified test method for power feedback governors requires further work [7].

# 6. IDENTIFIED ISSUES, PROPOSED SOLUTIONS AND FUTURE WORK

During the development of the requirements several issues were highlighted. In this chapter some of the issues and suggestions for future work are described. For some of the challenges possible solutions are explained.

## 6.1 ISSUE 1: FEW UNITS QUALIFY THE STABILITY REQUIREMENT

In the simulations it is obvious that a large share of the parameter sets is disqualified due to the stability requirement. A major reason for this is the scaling factor $\frac{\Delta \mathrm{P}_{\mathrm{ss}}}{C_{\mathrm{FCR-D}}}$ due to the required performance. If a unit performance is below the reference performance, the unit will have a lower capacity compared to its full steady state activation. This is taken into consideration when evaluating the stability.

In practise this means that units with significantly worse performance than the reference performance will have problems to qualify for stability. Both requirements are based on the system needs and are necessary to ensure adequate system performance. This problem can be mitigated by adjusting the droop so that the scaling factor is close to one.

Because of the difficulty to comply with the stability requirement and the capacity scaling due to the required performance, the available capacity from the units will reduce compared to current situation. It is very hard to estimate in detail how much the requirements will affect the available capacity. However, real tests performed indicate that on some units the capacity will be reduced significantly at high loadings. The tests together with simulation results show that unit capacity will often become rather much dependent on the unit loading whereas with the current requirements it is often possible to tune the unit to have the same capacity at nearly all loadings. As real unit performance is very dependent on the loading, it is only natural that the capacity varies with the loading with the new requirements.

If the available capacity is considered to be reduced too much there are several possible solutions available. All solutions have specific downsides to the benefit of getting more capacity into the system.

### SOLUTION 1.1: INCREASE CONSTRAINT OF KINETIC ENERGY

One solution is to increase the dimensioning kinetic energy. This will affect the open loop input signal, the result from the closed loop simulations of the minimum instantaneous frequency and also the KPI tables. The new KPI tables will provide a more relaxed requirement. Increasing the kinetic energy will make it easier to fulfil both the performance and the stability separately. The unit's capacity won't be scaled as much and the increased system inertia will make it easier to stay outside the stability margin in the Nyquist diagram.

The major downside with increasing the kinetic energy is the fact that the stability margin is only ensured down to the dimensioning kinetic energy level. When the real power system inertia decreases below this level, measures must be taken in order to reduce the regulating strength to maintain the stability margin. Then, other measures must be taken to deliver the needed active power response. One example is to make sure that active power response that does not affect stability negatively (for example from loads or HVDCs) is available to handle the missing part of the power imbalance in case of a major disturbance. These alternatives are investigated in *Future System Inertia 2* project of Nordic Analysis Group (2016-2017).

**SOLUTION 1.2: REDUCE FCR-D PERFORMANCE CONSTRAINT**

By reducing the performance constraint the intention is that not hydro power alone is responsible to handle the largest disturbance in the system without exceeding 49.0 Hz. Comparing to solution 1.1 when not increasing the inertia, the stability can be guaranteed down to 120 GWs without any further measures.

By decreasing the frequency limit to for example 48.9 Hz the performance requirement will be looser and the unit capacity will not be scaled as much as using 49.0 Hz. The reduced scaling will make it easier to qualify the stability requirement. By reducing the performance constraint, only the performance requirement will be directly affected, the stability requirement will be the same as before.

The downside with this solution is the fact that some other service or protection is needed to ensure a frequency above 49.0 Hz. At what inertia this other service is needed must be investigated and depends on the performance constraint.

**SOLUTION 1.3: INTRODUCE BLOCKING TIME PARAMETERS**

With blocking time parameters the intention is to run the turbine governor with a set of parameters during a limited time after a disturbance, before switching to another parameter set. This makes it possible to use a more aggressive and maybe even unstable parameter set when a major disturbance occurs. After a limited time the governor shall switch back to a slower and stable parameter set. By introducing this type of parameter switch it will be easier for the units to fulfil the performance requirement due to the aggressive parameters. The stability is then evaluated using the second parameter set.

The main challenge with this method is to decide duration and time of change from one parameter set to another and at the same time ensure system stability. With this approach, more complex turbine governor logics together with reprogramming of the governors are needed

## 6.2 ISSUE 2: CHANGE OVER FROM FCR-N TO FCR-D

One challenge is the transition between FCR-N and FCR-D. How a unit should switch over from one product to the other must be further studied in order to ensure that there are not problems if the units change parameters. One identified question is how often FCR-D parameters can and should be activated. If aggressive parameters are activated and deactivated several times during a short period of time, it may introduce oscillations in the waterways and cause wear and tear of the mechanical equipment.

Furthermore, simulations and real tests show that typically higher droop is needed for FCR-D than for FCR-N in order to comply with the FCR-D stability requirement. On the other hand, if change over parameters are used, FCR-D droop cannot be higher than FCR-N droop in order not to decrease FCR-N activation when switching to FCR-D parameters.

**SOLUTION 2.1: ROCOF BASED CHANGE OVER**

The issue with too many FCR-D activations can be mitigated by RoCoF based activation that activates FCR-D response only when RoCoF exceeds certain threshold value. With such scheme, it is possible to activate FCR-D only when it is actually needed, that is during severe disturbances.

The issue with RoCoF based activation is that good frequency measurement device is needed to detect the RoCoF quickly and accurately. Currently many frequency measurement devices are rather slow at capturing frequency changes which causes delays to the RoCoF measurements.

**SOLUTION 2.1: SEPARATE PID-CONTROLLERS FOR FCR-N AND FCR-D**

The problems with parameter change-over can be avoided with separate PID-controllers for FCR-N and FCR-D. The drawback is that turbine governor reprogramming is required. In many senses it would be preferred to have separate PID-controllers for FCR-N and FCR-D as then the FCR-N and FCR-D controls are more separated on the controller level and the provision of these two services becomes more clearly separated.

## 6.3 ISSUE 3: INTERACTIONS BETWEEN FAST AND SLOW UNITS

A possible issue in need of further studies is the interaction between fast and slow units and how that may affect the system performance. This must be studied in order to ensure there is no unexpected behaviour when a very fast unit provides FCR-D together with a slow unit with very high $\frac{\Delta P_{\mathrm{ss}}}{C_{\mathrm{FCR-D}}}$ ratio.

## 6.4 FUTURE WORK

The power system and the FCR providing units were studied using one-mass equivalents with simplified power system representation. There is a need to verify the design in a full-scale simulation environment where generators and loads are not lumped, power system components are included and the effect of voltage dynamics can be studied. Especially, it is important to study the effect of load voltage dependency for different locations of the generation unit/HVDC trip and at different load flow situations in the system.

RoCoF based FCR-D activation and blocking times on turbine governors also need to be carefully studied. These schemes must be carefully coordinated and designed in order not to cause any stability issues and to guarantee sufficient performance. Furthermore, the effect of high backlash on sine tests with a low excitation amplitude on units operating with high droops needs to be studied.

# 7. CONCLUSIONS

The work carried out within the framework of FCR-D revision has developed new requirements to fulfil the goals. The requirements put forward for FCR-D are based on the system needs in terms of closed loop stability and dynamic performance. The stability and performance requirements have been mapped to response in open loop testing in order to enable local testing at a unit. The closed loop stability requirement can be tested locally by sine test. Response at different time periods can be plotted in the Nyquist diagram, together with the system response, where the loop gain is scaled with the capacity coming from the results of the performance testing. It has been shown that there exists a strong correlation between the results in open loop ramp testing and the success of keeping the frequency above 49.0 Hz for the dimensioning incident. The requirements are put forward on delivered energy and power after five seconds from initiating the ramp of the frequency signal. The ramp rate is derived from the dimensioning kinetic energy system and verified by non-linear simulations. Any performance is accepted, however, the capacity (and thereby payment) will be scaled accordingly. Full capacity is determined by the steady-state capacity that is the power delivered at a frequency of 49.5 Hz. In addition, units with poor dynamic performance may find it hard to fulfil the stability requirement as the regulating strength is scaled with the unit capacity scaling factor and it has significant impact on stability.

# 8. REFERENCES

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# 9. APPENDIXES

Appendix 1: KPI tables

Appendix 2: Simulation model and scripts used in the studies