European Network of
Transmission System Operators
for Electricity

Supporting Document on Technical Requirements for Frequency Containment Reserve Provision in the Nordic Synchronous Area

Draft 2017

Prequalification Working Group, FCP project

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THIS IS A SUPPORTING DOCUMENT FOR THE NEW TECHNICAL REQUIREMENTS FOR FCR IN THE NORDIC SYNCHRONOUS SYSTEM.

THE REQUIREMENTS ARE SO FAR DRAFT REQUIREMENTS AND ARE THUS NOT REQUIREMENTS TO BE FULFILLED FOR CURRENT NORDIC FCR MARKET.

Contents

Definitions

Activated capacity	Part of the active power output caused by FCR activation
aFRR	Automatic Frequency Restoration Reserve
ENTSO-E	European Network of Transmission System Operators for Electricity
FCP	Frequency Containment Process
FCR	Frequency Containment Reserve
FCR-D	Frequency Containment Reserve for Disturbance
FCR-N	Frequency Containment Reserve for Normal operation
FCR provider	Legal entity providing FCR services from at least one FCR providing unit or group
Controller parameter set	A set of preselected parameter values, selectable with a single signal, e.g. a certain parameter set for island operation and another one for FCR-N
mFRR	Manual Frequency Restoration Reserve
Maintained capacity	The amount of reserve in MW that will be utilized at full activation, FCR-N 50±0.1Hz, FCR-D at 49.5 Hz for upwards regulation and 50.5 Hz for downwards regulation
Prequalification	Prequalification means the process to verify the compliance of an FCR providing unit or an FCR providing group with the requirements set by the *Technical Requirements for Frequency Containment Reserve Provision in the Nordic Synchronous Area*
Providing entity	FCR Providing Unit or FCR Providing Group
Providing group	FCR Providing Group means an aggregation of Power Generating Modules, Demand Units and/or Reserve Providing Units and/or Energy storages connected to more than one Connection Point fulfilling the requirements for FCR
Providing unit	FCR Providing Unit means a single or an aggregation of Power Generating Modules and/or Demand Units and/or Energy storages connected to a common Connection Point fulfilling the requirements for FCR
SO GL	ENTSO-E System Operation Guideline
TSO	Transmission System Operator
Setpoint	Part of the active power output that does not include FCR activation

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1 Introduction

This document supports the Main document, *Technical Requirements for Frequency Containment Reserve Provision in the Nordic Synchronous Area*, aiming towards a common Nordic harmonization of the technical requirements for frequency containment reserves (FCR) within the Nordic power system.

First, abbreviations and terminology used in the Main document and throughout this document is explained. In Section 2, the frequency containment process (FCP) used in the Nordic power system is outlined. The mathematical representation of the dynamic behaviour of FCR providing entities used in verifying FCR providing entity's compliance to the requirements is explained in Section 3 to provide a better understanding on how entity's dynamic behaviour is evaluated. In Section 4, the prequalification process is explained. FCR capacity calculation for real-time telemetry and data logging purposes is explained in Section 5.

Appendices of this document include templates for application document, FCR-N & FCR-D test program, FCR-N & FCR-D test report and for logged data delivery. Also FCR-N & FCR-D test Excel sheets and an example prequalification package are provided.

The prequalification process will ensure that the FCR providers have the ability to deliver the specified product required by the TSO and that all necessary technical requirements are fulfilled. The need for a prequalification process in order to provide FCR products is also stated in the ENTSO-E System Operation Guideline (SO GL). The prequalification shall be performed before a provider can deliver FCR, and shall comprise documentation ensuring that the provider can deliver the specified product as required by the TSO.

2 The frequency containment process

The frequency containment process for the Nordic power system is illustrated in Figure 1 for an under-frequency situation (the figure describes stationary state). The situation is similar for an over-frequency situation.

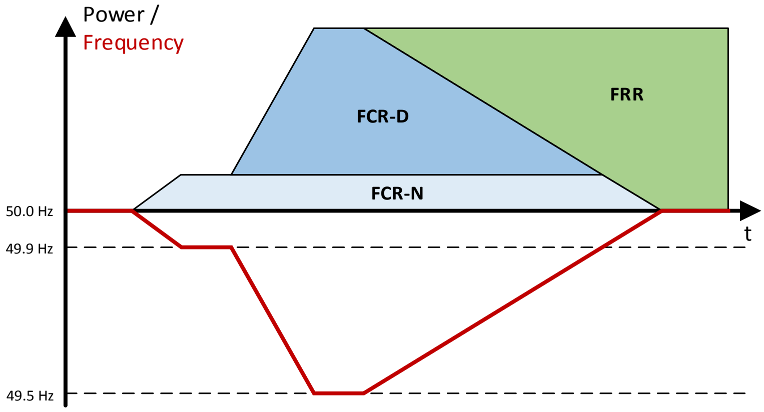

Figure 1: Frequency containment and frequency restoration processes

As frequency begins to decrease from the nominal value, 50.0 Hz, due to normal fluctuations in load and generation, FCR-N (Frequency Containment Reserve for Normal operation) begins to activate. FCR-N is fully activated at a frequency of 49.9 Hz. If the frequency continues to decrease beyond 49.9 Hz, for example, due to the loss of a large generator, FCR-D (Frequency Containment Reserve for Disturbances) begins to activate. FCR-D is fully activated at a steady state frequency of 49.5 Hz. Within 15 minutes the FCR-D should be fully restored by FRR (Frequency Restoration Reserve) and the system should be prepared for the next disturbance.

At first the **Frequency Containment Process** prevents the frequency from a further decrease. Products used in this process are called FCR-N and FCR-D, and they are activated within seconds to minutes from a detected frequency deviation.

At second the **Frequency Restoration Process** brings back the frequency close to 50.0 Hz. Products used in this process are called FRR, and are further divided into automatically and manually activated products (aFRR and mFRR). These products have to be activated within minutes.

The FCR products are all fully automatically activated by control units, e.g. governors, which measure the grid frequency and adjust the power of the control providing entities. An example could be an electrical boiler that normally heats water. If the frequency in the system increases, the local controller will detect a high frequency and will tell the boiler to increase the load, as a function of the frequency deviation.

Three FCR products are used in the Nordic synchronous area, FCR-N, FCR-D upwards and FCR-D downwards.

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3 Mathematical representation of the dynamic behaviour of FCR providing entities

A mathematical representation of the dynamic behaviour of an FCR providing entity is necessary in order to verify the compliance with the dynamic performance requirements and with the stability requirements. This mathematical representation, a set of transfer function values, is derived from sine and step response prequalification test data. A number of different time period specific transfer function values are used to describe the dynamic behaviour of an FCR providing entity. The transfer function values are calculated for each of the sine tests with different time periods listed in the Main document.

Each of these transfer function values describes the relation between the frequency input and the change in power output of the FCR providing entity when subjected to a sinusoidal input frequency signal with a certain time period. Visual representation of these transfer function values is referred to as FCR-vectors.

3.1 Transfer function values

A transfer function value (transfer function evaluated for a certain time period / angular frequency) is defined as the gain that describes the magnification of the output and the phase that describes the phase shift of the output, relative to the input signal. This magnification and phase shift are dependent on the time period / angular frequency. Therefore, in order to describe the dynamics of the FCR providing entity, multiple transfer function values need to be calculated for different time periods.

The angular frequency corresponding to a certain time period (T) can be calculated as

$$\omega = \frac{2\pi}{T} \tag{3.1}$$

Figure 3 illustrates how these transfer function values can be calculated from the test data and how the transfer function values can be used to draw a Bode plot[1] of the FCR providing entity.

The non-normalized gain of the transfer function for angular frequency ω can be calculated as

$$|\boldsymbol{FCR}(\boldsymbol{j}\omega)| = \frac{A_{\mathrm{P}}}{A_{\mathrm{f}}} \tag{3.2}$$

where A_{P} is the amplitude of the measured sinusoidal power signal with an angular frequency of ω, and A_{f} is the amplitude of the injected sinusoidal frequency modulation. This gain is then normalized to make the transfer function value nondependent of the FCR capacity of the entity. The normalization is defined so that the static gain shall be equal to 1 p.u.

$$|\boldsymbol{F}(\boldsymbol{j}0)| = 1.00\ \mathrm{p.u.} \tag{3.3}$$

Hence, the normalized gain of the transfer function for angular frequency ω can be calculated as

$$|\boldsymbol{F}(\boldsymbol{j}\omega)| = \frac{|\boldsymbol{FCR}(\boldsymbol{j}\omega)|}{e} \tag{3.4}$$

where e is the normalization factor obtained from a step response measurement. Ideally the normalization factor would be equal to the stationary power change (ΔP**)** caused by the step in frequency divided by the amplitude of the applied frequency step (A_{step})

[1] A Bode plot is a visual representation of the frequency response of a system (for example, an FCR providing entity)

$$e = \frac{\Delta P}{A_{\text{step}}} \quad (3.5)$$

However, FCR providing entities controlled via mechanical equipment like hydro power units, typically have backlash in their control system. This backlash will make the normalization factor dependent on previous position changes of the control system. Also, backlash visible on the sine test measurements would not be properly taken into account when normalizing the response. In order to take this into account the normalization factor is calculated according to the procedure outlined in Section 3.2

The phase φ (in degrees) of the transfer function for a certain angular frequency / time period can be calculated as

$$\phi = \mathbf{Arg}(\boldsymbol{F}(j\omega)) = \Delta t \frac{360°}{T} \quad (3.6)$$

where T is the time period (s) and Δt is the time difference (s) of the input (frequency) signal and output (power) signal, as shown in Figure 3.

3.2 Calculation of FCR normalization factor

At first, the average of the active power step response, outlined in Section 4.4.1 of the Main document and shown in Figure 2, is calculated without any contribution from the backlash according to

$$\Delta P_{NO-Backlash} = \frac{|\Delta P_1| + |\Delta P_3|}{2} \quad (3.7)$$

Then, the total backlash in per unit is calculated as

$$2D_{pu} = \frac{||\Delta P_1| - |\Delta P_2|| + ||\Delta P_3| - |\Delta P_4||}{2\ \Delta P_{NO-Backlash}} \quad (3.8)$$

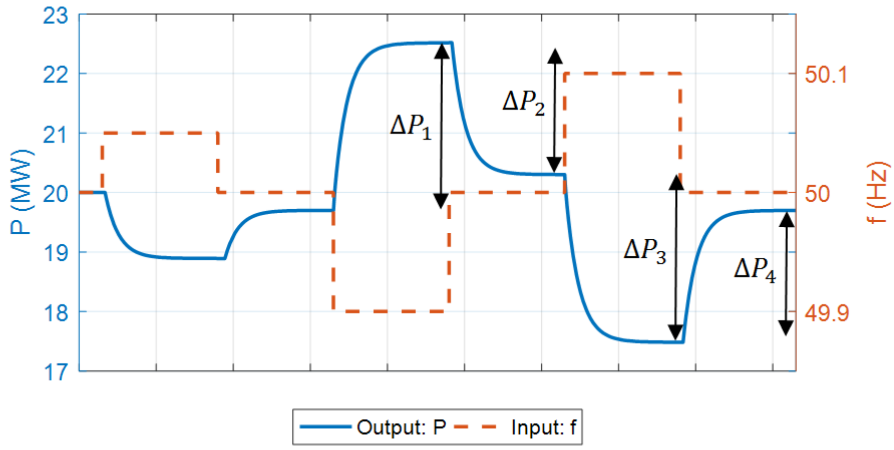


Figure 2: FCR-N step response sequence

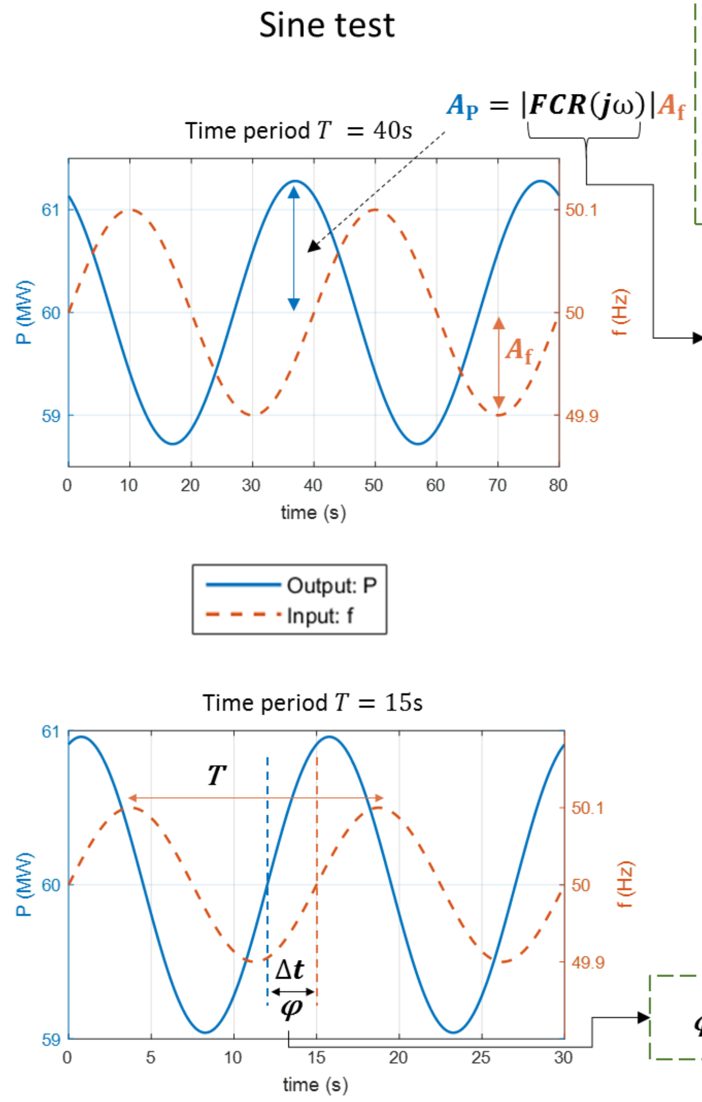
The total backlash is not allowed to be above 0.3 p.u. Based on the total backlash in per unit ($2D_{pu}$), the backlash scaling factor h is obtained from Table 1.

Table 1: Backlash scaling factor (h) as a function of total backlash in per unit ($2D_{pu}$)

$2D_{pu}$	0.00	0.01	0.02	0.03	0.04	0.05	0.06
h	1	0.999	0.998	0.997	0.996	0.994	0.992
$2D_{pu}$	0.07	0.08	0.09	0.10	0.11	0.12	0.13
h	0.99	0.988	0.986	0.984	0.981	0.979	0.976
$2D_{pu}$	0.14	0.15	0.16	0.17	0.18	0.19	0.20
h	0.974	0.971	0.968	0.965	0.962	0.959	0.956
$2D_{pu}$	0.21	0.22	0.23	0.24	0.25	0.26	0.27
h	0.953	0.95	0.946	0.943	0.94	0.936	0.932
$2D_{pu}$	0.28	0.29	0.30				
h	0.929	0.925	0.921				

Finally, the normalization factor e can be calculated, based on an A_{step} of 0.1 Hz, as

$$e = \frac{h \cdot \Delta P_{NO-Backlash}}{A_{\text{step}}} \tag{3.9}$$



Sine tests are used to find out gain and phase at discrete time periods which in turn can be used to construct a Bode plot

$F(j\omega)$ = normalized $FCR(j\omega)$, i.e. $|F(j0)| = 1.00$pu

T (s)	Gain $\lvert F(j\omega)\rvert$ (p.u.)	Phase Arg($F(j\omega)$) (°)
10	0.10	57
15	0.12	72
25	0.15	112
40	0.16	117
50	0.20	120
60	0.21	123
70	0.22	126
90	0.27	132
150	0.32	143
300	0.55	146

$$\varphi = \mathrm{Arg}(F(j\omega)) = \Delta t \frac{360°}{T}$$

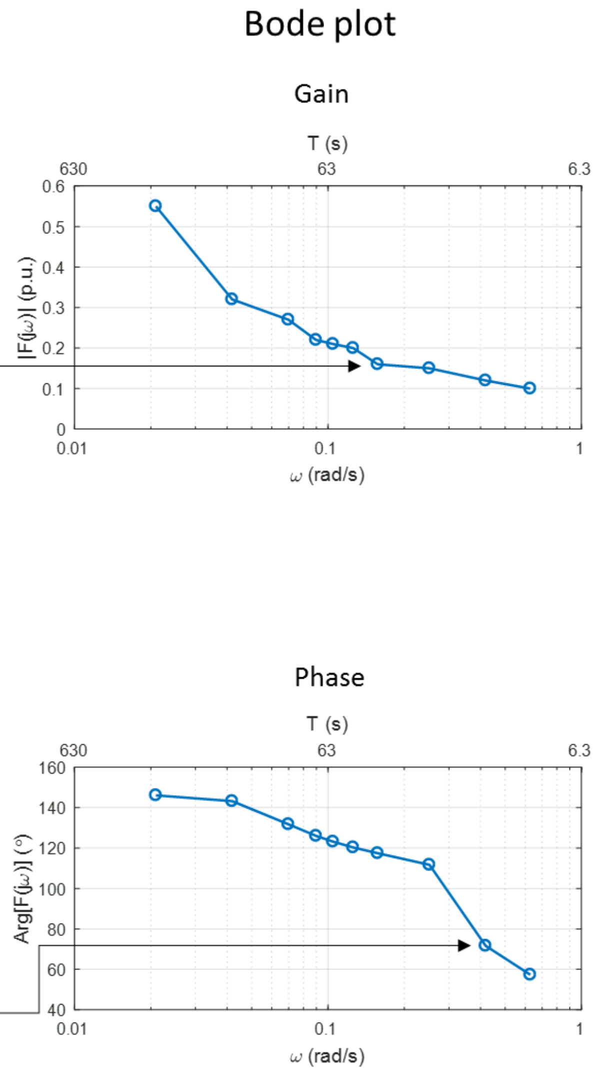


Figure 3: Sine tests, transfer function values and Bode plots.

3.3 FCR-vectors

Figure 4 illustrates how the transfer function values can be visualized as FCR-vectors. The FCR-vectors are plotted in a complex plane having an imaginary axis (y) and a real axis (x). The vectors always start from the origin, point (0, 0). The length of the vector equals the gain of the corresponding transfer function value and the angle of the vector equals the phase of the corresponding transfer function value. Alternatively, FCR-vectors can be defined by the (x, y)-coordinates of their end points. The x-coordinate (real part of the transfer function value) can be calculated from the gain and phase of the transfer function value as

$$x = |F(\mathrm{j}\omega)| \cos\left[\mathrm{Arg}(F(\mathrm{j}\omega))\right] \tag{3.10}$$

and the y-coordinate (imaginary part of the transfer function value) can be calculated as

$$\mathrm{y} = |\mathrm{F}\,(\mathrm{j}\omega)| \sin\left[\mathrm{Arg}(\mathrm{F}\,(\mathrm{j}\omega))\right] \tag{3.11}$$

The requirement circles (dynamic performance and stability) can be plotted in the same complex planes.

> *NOTE*
>
> When calculating the transfer function values from the test data, Fourier-transform or Least-Squares-Sinusoidal-Fit shall be used to identify the transfer function values. Final compliance verification is to be performed using an application provided by the TSO.

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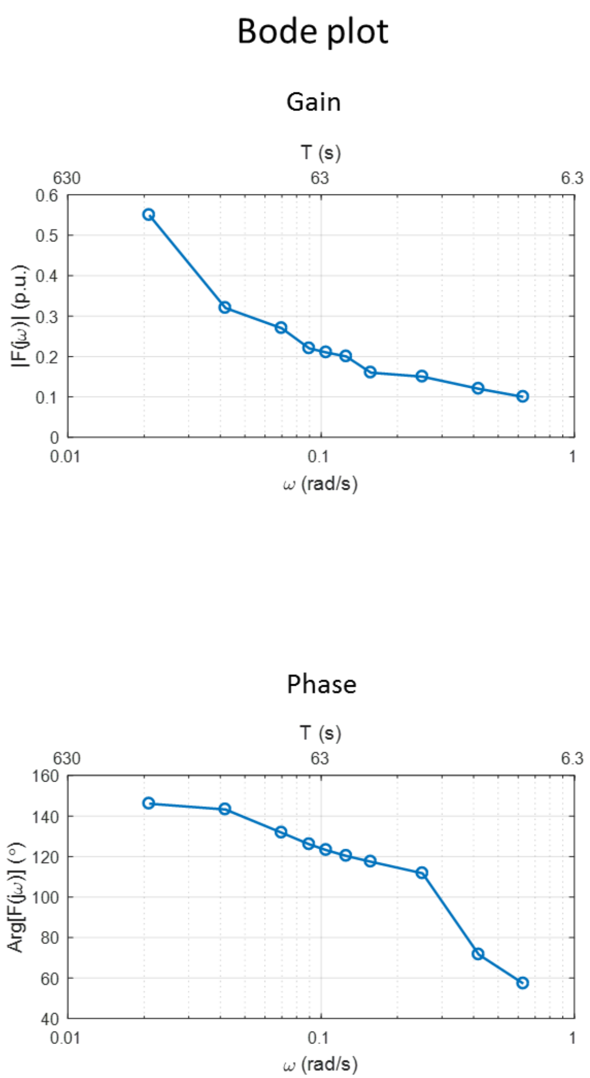

The information in the table and presented in the bode plot, can be projected into complex planes. The requirements are visualized on complex planes

$$x = |F(j\omega)| \cos[\text{Arg}(F(j\omega))]$$
$$y = |F(j\omega)| \sin[\text{Arg}(F(j\omega))]$$

T (s)	Gain |F(jω)| (p.u.)	Phase Arg(F(jω)) (°)	Real part x	Imaginary part y
10	0.10	57	0.05	0.08
15	0.12	72	0.04	0.11
25	0.15	112	-0.06	0.14
40	0.16	117	-0.07	0.14
50	0.20	120	-0.10	0.17
60	0.21	123	-0.11	0.18
70	0.22	126	-0.13	0.18
90	0.27	132	-0.18	0.20
150	0.32	143	-0.26	0.19
300	0.55	146	-0.46	0.31

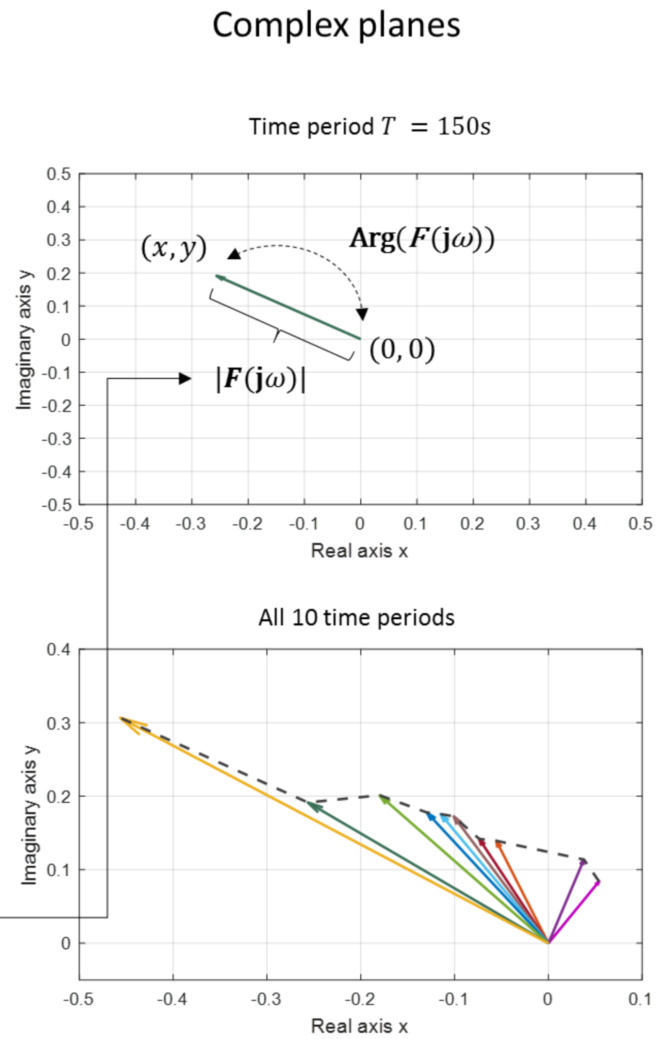

Figure 4: Bode plots, transfer function values, FCR-vectors and complex planes.

4 The prequalification process

Delivery of FCR by an FCR provider requires that the corresponding FCR providing entity is prequalified. The prequalification process is harmonized between the Nordic TSOs, and it is based on the requirements given to the TSOs through the European guidelines from the European Commission[2]. This guideline states that the prequalification shall consist of the submission of the formal application of the potential FCR provider including all required information to the reserve connecting TSO. The procedures for the evaluation of the provided information by the reserve connecting TSO, for the announcement of the respective findings including the possibility for the FCR provider to amend the provided information within a defined period of time, and for the acceptance or refusal of the application by the reserve connecting TSO, are also stated in the SO GL. The prequalification process is illustrated in Figure 5.

The prequalification shall ensure that the FCR provider is capable to provide FCR in accordance with the requirements from the TSO. The process shall also ensure that the respective TSO has all the necessary documentation for the FCR providing entities. Furthermore, the process must ensure that the correct communication links are established and that the required telemetry is received. The required tests, documentation and data are further described in this document and stated in the Main document.

[2] System Operation Guideline (SO GL), part IV LFC&R, version 4 May 2016

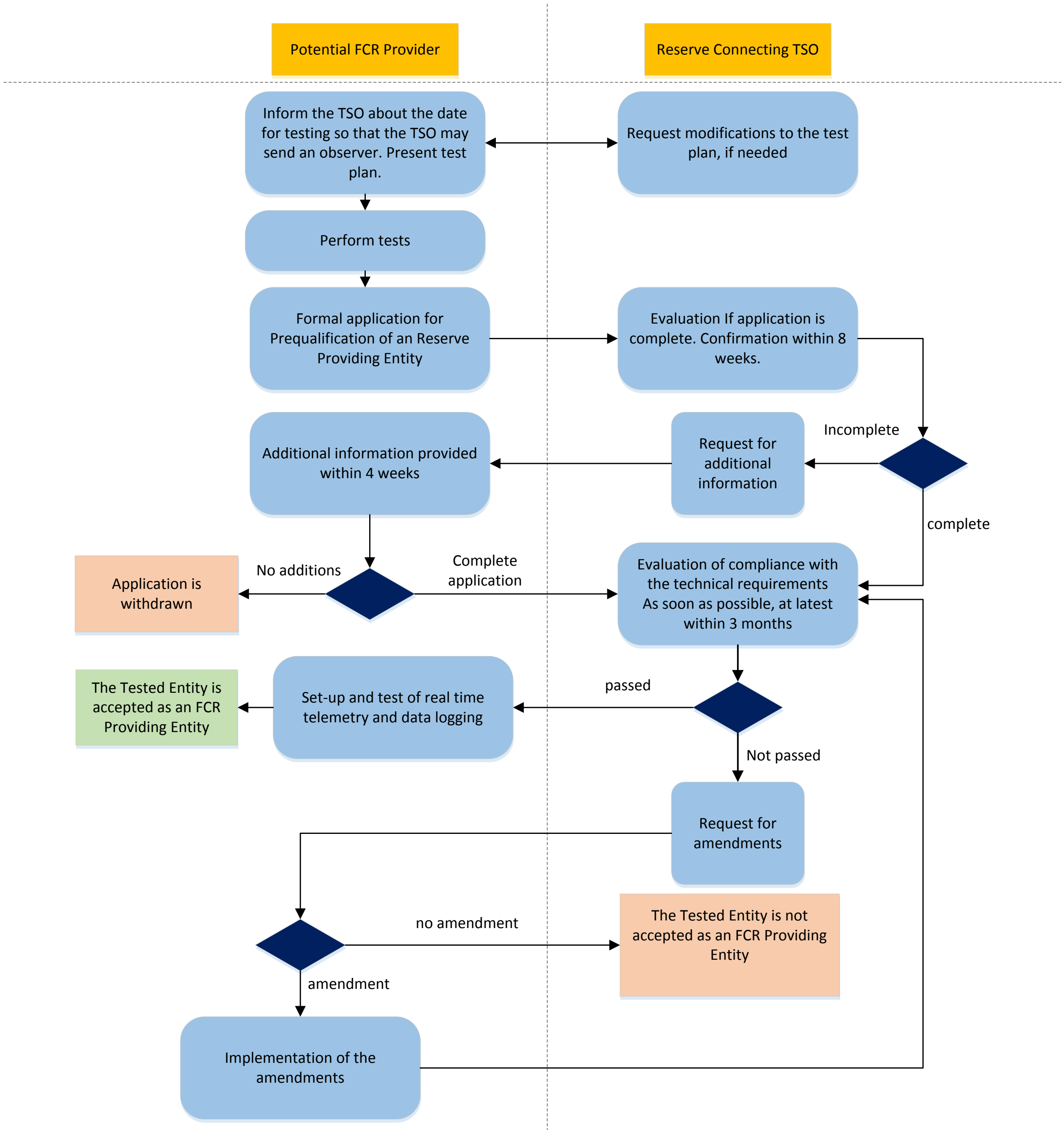

Figure 5: Illustration of the steps in the prequalification process.

4.1 Test procedure

The FCR providing entity shall be synchronized to the grid during the test. During testing, supplementary active power controls like aFRR shall be disabled so that the setpoint remains unchanged. The control signal is replaced by a synthetic signal according to Figure 6.

The step response tests are performed to determine the capacity and stationary performance, and the sine tests are performed to verify the performance and the stability of the FCR-N and FCR-D providing entities.

Simulations are recommended for assisting in tuning of entities that are difficult and time consuming to tune in order to faster determine the parameters for which the requirements are met.

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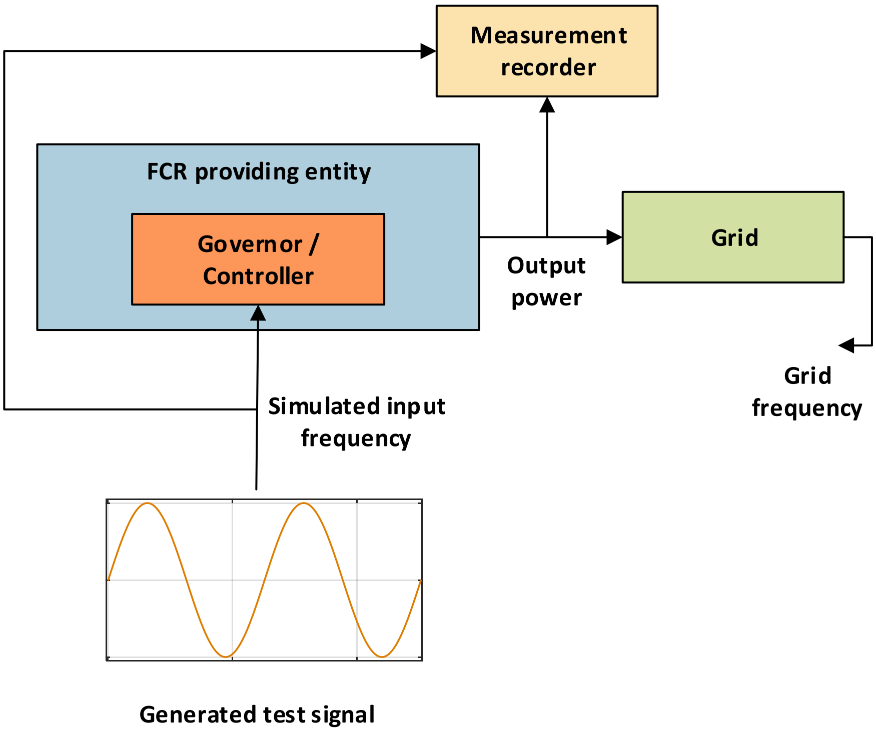

Figure 6: Principle test setup.

If the FCR providing entity being tested is equipped with a Power System Stabilizer (PSS) that interacts with FCR activation, the PSS shall be disabled while performing the tests.

4.2 Verification of FCR-N dynamic performance requirement

Compliance with the FCR-N dynamic performance requirement is verified using a diagram shown in the Main document. The requirement curve is defined as the absolute value of the inverse of the transfer function of the expected system active power disturbance profile, that is

$$\left|\frac{1}{\frac{1}{70\mathbf{s}+1}}\right| \tag{4.1}$$

where
$\boldsymbol{s}$ is the Laplace operator

Furthermore, the requirement function is scaled by a factor of 1.05 in order to account for measurement uncertainty. The unit response combined with the representation of the power system (that needs to have smaller value than the value of the dynamic performance requirement function) is given by

$$\left|\frac{\mathbf{G}(\mathbf{s})}{1-\mathbf{F}(\mathbf{s})\mathbf{G}(\mathbf{s})}\right| \tag{4.2}$$

where $\mathbf{G}(\mathbf{s})$ is

$$\frac{600\ \text{MW}}{0.1\ \text{Hz}}\frac{f_0}{S_{\text{n,nom}}}\frac{1}{2H_{\text{nom}}\boldsymbol{s}+K_{\text{f,nom}}*f_0} \tag{4.3}$$

f_0 is 50 Hz
$S_{\mathrm{n,nom}}$ is 42 000 MW
H_{nom} is $\frac{190\ 000\ \mathrm{MWs}}{S_{\mathrm{n,nom}}}$

$K_{\mathrm{f,nom}}$ is 0.01 (the load frequency dependence)

and $\mathbf{F}(\boldsymbol{s})$ is defined by the FCR-vectors.

The dynamic performance requirement can also be illustrated using circles in complex planes. This way of visualizing the requirement may be helpful when tuning the controller.

The requirement is met when all the FCR-vectors point outside the pre-defined performance requirement circles. The performance requirement circle centre coordinates and the circle radiuses are listed in Table 2. The circles are visually represented in Figure 7 together with the FCR-vectors of an example unit.

The circles are only indicative and the final verification of the dynamic performance has to be performed using the diagram shown in the Main document. FCR-vectors pointing outside the circles only guarantee that the requirement is met at the corresponding discrete time periods whereas the dynamic performance requirement is continuous in between time periods from 10 s to 300 s.

Table 2: Centre coordinates and radiuses for dynamic performance requirement circles

Time period (s)	Circle centre (x, y)[3]	Circle radius (p.u.)
10	(0.070, 0.796)	0.025
15	(0.070, 0.531)	0.038
25	(0.070, 0.318)	0.062
40	(0.070, 0.199)	0.098
60	(0.070, 0.133)	0.143
70	(0.070, 0.114)	0.164
80	(0.070, 0.099)	0.184
100	(0.070, 0.080)	0.220
150	(0.070, 0.053)	0.299
400	(0.070, 0.020)	0.576

[3] where x corresponds to the real part and y corresponds to the imaginary part

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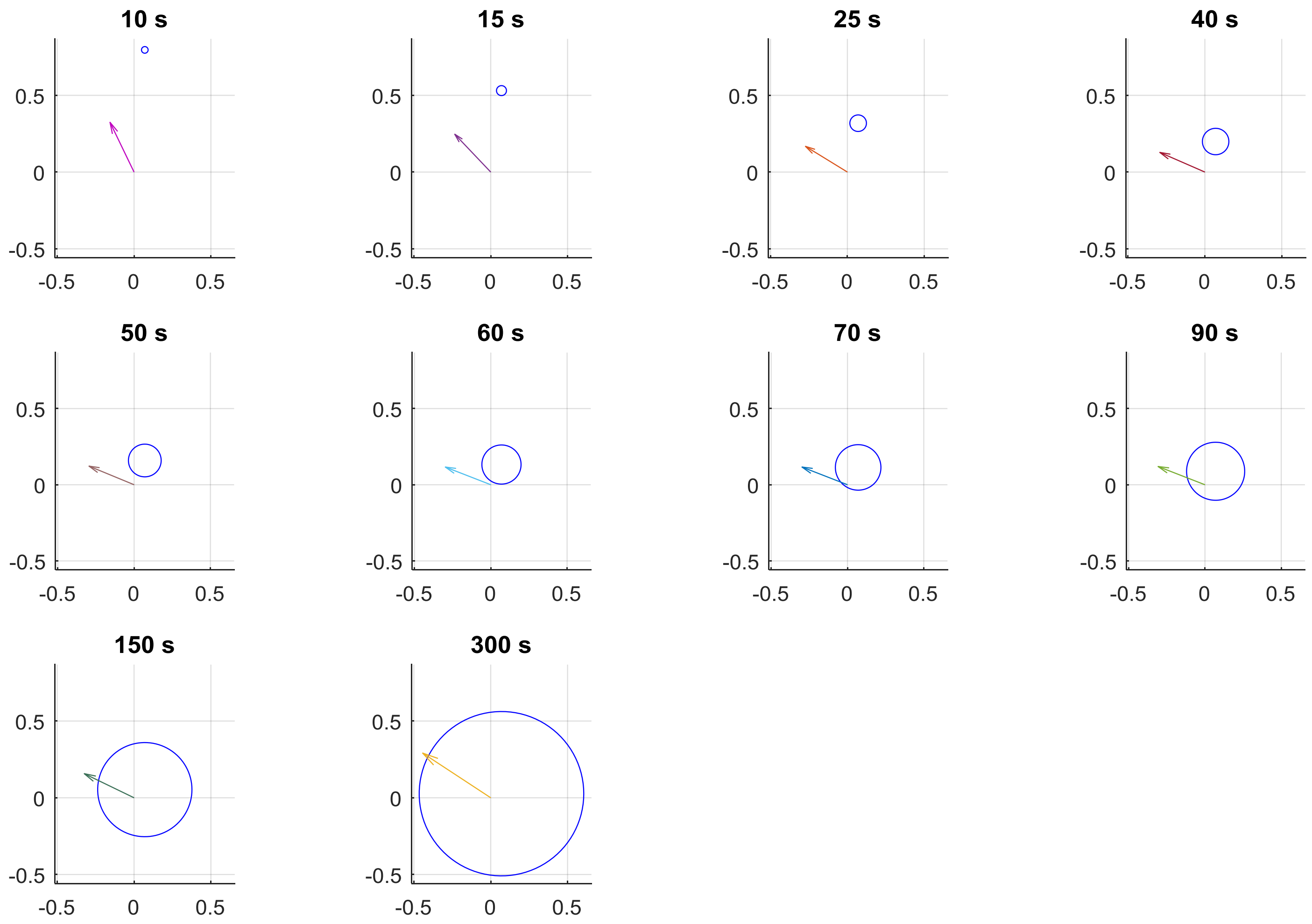

Figure 7: FCR-N dynamic performance requirement circles and FCR-vectors of an example unit

4.3 Verification of FCR stability requirement

Further information on the method for verifying compliance with FCR-N and FCR-D stability requirement is provided in this section.

For FCR-N and FCR-D, the radius of the stability margin circle shown in the Main document is 0.411 p.u.

4.3.1 FCR-N

Compliance with the FCR-N stability requirement is verified using Nyquist diagram as outlined in the Main document. To obtain the Nyquist curve, the FCR-vectors shall be multiplied with the grid transfer function

$$-\frac{600\ \mathrm{MW}}{0.1\ \mathrm{Hz}}\frac{f_0}{S_{\mathrm{n,wc}}}\frac{1}{2H_{\mathrm{wc}}\boldsymbol{s}+K_{\mathrm{f,wc}}*f_0} \tag{4.4}$$

where
$S_{\mathrm{n,wc}}$ is 23 000 MW
H_{wc} is $\frac{120\ 000\ \mathrm{MWs}}{S_{\mathrm{n,wc}}}$
$K_{f,\mathrm{wc}}$ is 0.005 (the load frequency dependence)

Requirement on stability margins can also be illustrated using circles in complex planes. This way of visualizing the requirement may be helpful when tuning the controller.

The stability margin is sufficient when all the FCR-vectors point outside the pre-defined stability requirement circles. The stability circle centre coordinates and circle radiuses are listed in Table 3. The circles are visually represented in Figure 8 together with the FCR-vectors of an example unit.

The circles are only indicative and final stability verification has to be performed using a Nyquist diagram. FCR-vectors pointing outside the circles only guarantee that the stability margins are sufficient at discrete time periods, not that the system is stable. Hence, it is possible to have an unstable system even though the FCR-vectors are pointing outside the stability circles. Also, the stability requirement is continuous, not discrete. Therefore, the stability requirement verification using Nyquist diagram is needed.

Table 3: Centre-coordinates and radiuses of stability requirement circles

Time period [s]	Circle centre (x, y)[4] [p.u., p.u.]	Circle radius [p.u.]
10	(0.019, 0.503)	0.207
15	(0.019, 0.335)	0.138
25	(0.019, 0.201)	0.083
40	(0.019, 0.126)	0.052
50	(0.019, 0.101)	0.042
60	(0.019, 0.084)	0.035
70	(0.019, 0.072)	0.031
90	(0.019, 0.056)	0.024
150	(0.019, 0.034)	0.016
300	(0.019, 0.017)	0.010

[4] where x corresponds to the real part and y corresponds to the imaginary part

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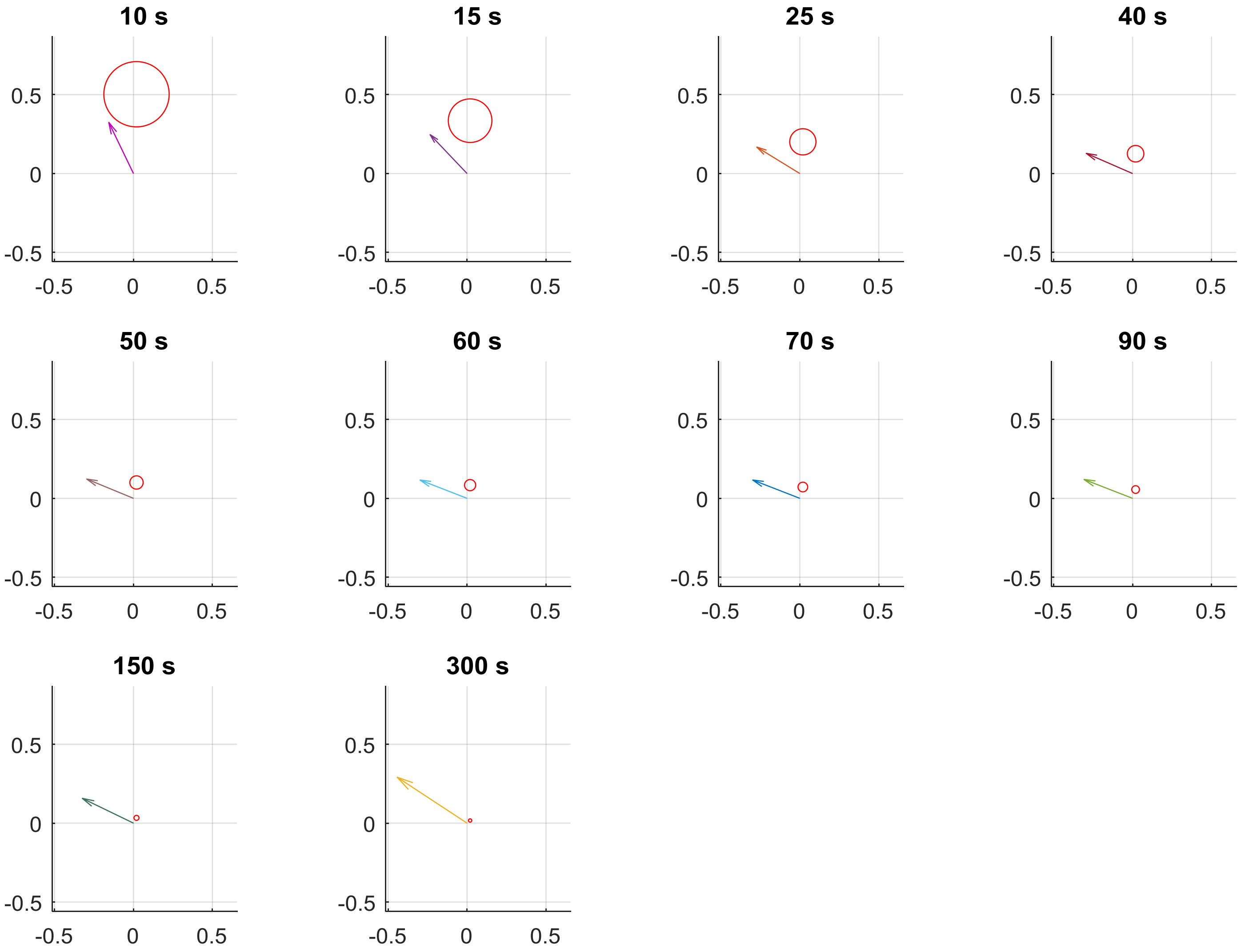

Figure 8: FCR-N stability requirement circles and FCR-vectors of an example unit.

4.3.2 FCR-D

Compliance with the FCR-D stability requirement is verified using Nyquist diagram as outlined in the Main document. To obtain the Nyquist curve, the FCR-vectors shall be multiplied with the grid transfer function

$$-\frac{\Delta P_{\mathrm{ss}} * 1450\ \mathrm{MW}}{C_{\mathrm{FCR-D}} * 0.4\ \mathrm{Hz}} \frac{f_0}{S_{\mathrm{n,wc}}} \frac{1}{2H_{\mathrm{wc}}\boldsymbol{s} + K_{\mathrm{f,wc}} * f_0} \tag{4.5}$$

where

$C_{\mathrm{FCR-D}}$ is the FCR-D capacity calculated according to the formula in the Main document
ΔP_{ss} is the steady state FCR-D activation when the entity is subjected to a frequency input step from 49.9 Hz to 49.5 Hz or from 50.1 Hz to 50.5 Hz, for FCR-D upwards and downwards respectively, as outlined in the Main document.

FCR-vectors are normalized in the same way as for FCR-N (FCR-N step response sequence needs to be applied). If FCR-D is provided using the same controller parameters as FCR-N, it is possible to use the FCR-N FCR-vectors for FCR-D stability verification. However, compliance with FCR-N stability requirement does not mean that also FCR-D stability requirement is fulfilled!

4.4 Prequalified FCR capacity determination

The method for calculating the FCR-N and FCR-D capacities is outlined in this section.

4.4.1 FCR-N

The capacity of an FCR-N providing entity is determined based on the step response sequence measurement outlined in Subsection 4.4.1 of the Main document and shown in Figure 2.

First, the total backlash is calculated according to

$$\boldsymbol{2D} = \frac{||\Delta \boldsymbol{P_1}| - |\Delta \boldsymbol{P_2}|| + ||\Delta \boldsymbol{P_3}| - |\Delta \boldsymbol{P_4}||}{\boldsymbol{2}} \tag{4.6}$$

and then FCR-N capacity can be calculated with

$$\boldsymbol{C_{\mathrm{FCR-N}}} = \frac{|\Delta \boldsymbol{P_1}| + |\Delta \boldsymbol{P_3}| - \boldsymbol{2D}}{\boldsymbol{2}} \tag{4.7}$$

This is done at all tested setpoints.

4.4.2 Setpoints between the minimum and maximum setpoint

When the capacity is determined for both maximum ($\boldsymbol{P}(\mathrm{C}_{max})$) and minimum ($\boldsymbol{P}(C_{\min})$) setpoint where FCR is to be provided the capacity for all setpoints in-between can be interpolated in accordance with Equation (4.8), where C_{min} and C_{max} are determined by Equation (4.7) for FCR-N and according to calculations outlined in Section 3.2.2 of the Main document for FCR-D, for the minimum and maximum setpoint respectively.

$$\boldsymbol{C_{pre-qual}}(P_{\text{setpoint}}) = C_{min} + (C_{max} - C_{min})\frac{\boldsymbol{P_{setpoint}} - \boldsymbol{P}(C_{\min})}{\boldsymbol{P}(\mathrm{C}_{max}) - \mathbf{P}(\mathrm{C}_{min})}$$

$$\boldsymbol{C_{pre-qual}}(P_{setpoint}) = 0\ if \begin{cases} P_{setpoint} > 1.05 * \boldsymbol{P}(C_{max}) \\ P_{setpoint} < 0.95 * \boldsymbol{P}(C_{min}) \end{cases} \tag{4.8}$$

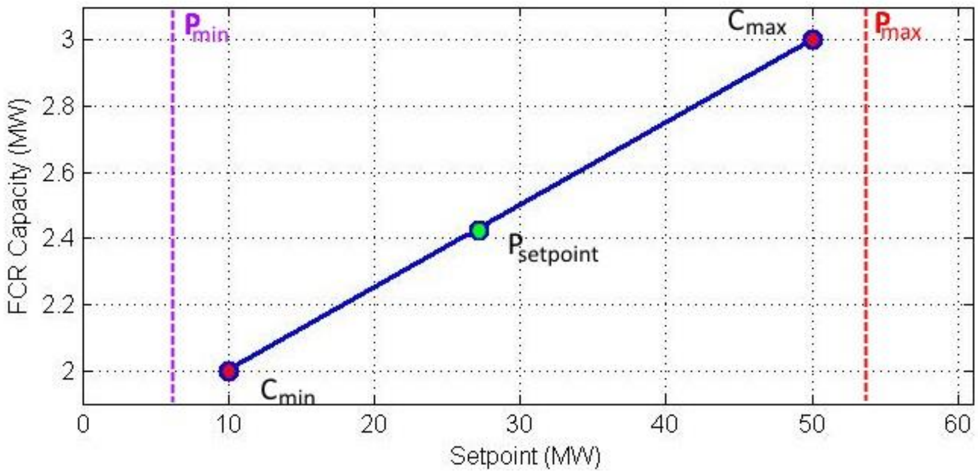

Figure 9: Linear interpolation to determine the capacity for setpoints between the minimum and maximum tested setpoint.

Once the maximum and minimum capacity are determined, as shown in Figure 9, the prequalified capacities in between can be calculated with Equation (4.8) as shown by the examples below.

$$\text{For a setpoint of 10 MW } C_{\text{pre-qual}}(10) = 2 + (3-2)\frac{10-10}{50-10} = C_{\min} = 2\ MW$$

$$\text{For a setpoint of 27 MW } C_{\text{pre-qual}}(27) = 2 + (3-2)\frac{27-10}{50-10} = 2{,}42\ MW$$

$$\text{For a setpoint of 50 MW } C_{\text{pre-qual}}(50) = 2 + (3-2)\frac{50-10}{50-10} = C_{\max} = 3\ MW$$

If the entity is tested at more than 2 setpoint values, the linear interpolation is done based on the two tested setpoint values in-between which the setpoint lies. This procedure is similar for FCR-N and FCR-D.

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5 FCR capacity calculation for real-time telemetry and data logging

The TSOs have to be able to monitor the capacity of maintained reserves in real-time in order to ensure operational security and to predict the behavior of the system. Access to logged data of the reserves enables the TSOs to ensure the quality of the product and precision in disturbance analysis as well as a possibility for providers to optimize their products.

Since maintained FCR capacity may be limited by the maximum power output (and by the minimum power output), the FCR-N and FCR-D capacity, as calculated in Section 4.4.2 has to be saturated accordingly. As the FCR capacity can vary with the setpoint and the setpoint may be changed during operation, the maintained capacity of the FCR needs to be recalculated accordingly.

The methods outlined in this section shall be used when calculating the maintained FCR capacity for real-time telemetry and data logging purposes if the provider does not have a more accurate method (the method needs to be approved by the TSO). For aggregated entities, aggregated values shall be reported to the TSO.

5.1 Maintained FCR-N capacity

The maintained FCR-N capacity (MW) can be calculated according to

$$\mathbf{C_{FCR-N}} = \mathbf{max}\left[\mathbf{min}\left(\mathbf{P_{max}} - \mathbf{P_{setpoint}}, \mathbf{P_{setpoint}} - \mathbf{P_{min}}, \mathbf{C_{pre-qual}}(\mathbf{P_{setpoint}})\right), \mathbf{0}\right] \quad (5.1)$$

where
$P_{\max}$ is the current maximum power output
$P_{\min}$ is the current minimum power output
$P_{\max}$ is the current power setpoint
$\boldsymbol{C}_{\mathbf{pre-qual}}(P_{\text{setpoint}})$ is calculated as in Equation (4.8)

This calculation is illustrated in Figure 10.

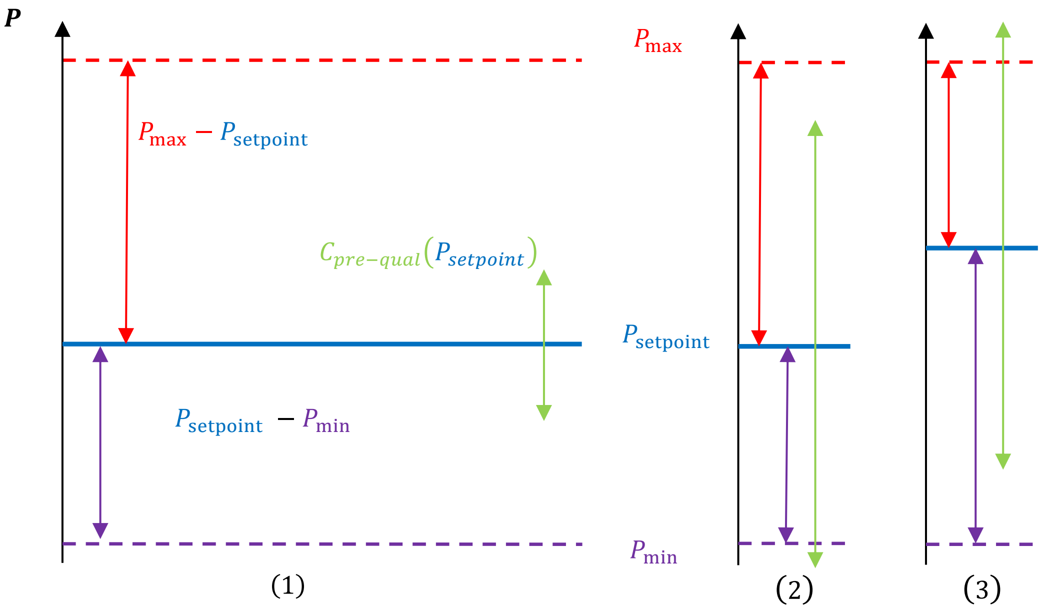

Figure 10: The three limits of FCR-N capacity for a unit which is limited either by prequalification test result (1), minimum active power (2) or maximum active power (3).

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$C_{\mathrm{FCR-N}}$ is zero when the frequency control is inactive.

5.2 Maintained FCR-D capacity

Maintained FCR-D capacity (MW), separately for upwards and downwards regulation can be calculated according to

$$\boldsymbol{C}_{\mathbf{FCR-D,upwards}} = \mathbf{max}\left[\mathbf{min}\left(\boldsymbol{P}_{\mathbf{max}} - \boldsymbol{P}_{\mathbf{setpoint}} - \boldsymbol{C}_{\mathbf{FCR-N}},\ \boldsymbol{C}_{\mathbf{pre-qual}}\left(\boldsymbol{P}_{\mathbf{setpoint}}\right)\right),\ \mathbf{0}\right] \quad (5.2)$$

$$\boldsymbol{C}_{\mathbf{FCR-D,downwards}} = \mathbf{max}\left[\mathbf{min}\left(\boldsymbol{P}_{\mathbf{setpoint}} - \boldsymbol{P}_{\mathbf{min}} - \boldsymbol{C}_{\mathbf{FCR-N}}, \boldsymbol{C}_{\mathbf{pre-qual}}\left(\boldsymbol{P}_{\mathbf{setpoint}}\right)\right), \mathbf{0}\right] \quad (5.3)$$

This calculation is illustrated in Figure 11.

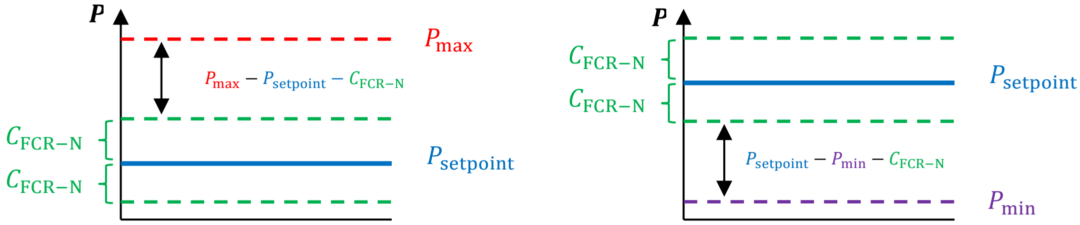

Figure 11: The limits of FCR-D capacity for a unit which is limited either by maximum active power or minimum active power while delivering FCR-N (FCR- D upwards in the left figure and FCR-D downwards in the right).

$C_{\mathrm{FCR-D,upward}}$ and/or $C_{\mathrm{FCR-D,downward}}$ is zero when the frequency control is inactive. The value of $C_{\mathrm{FCR-N}}$ is set to zero for an entity delivering only FCR-D.

5.3 FCR providing entities with limited activation capability

In addition to the maintained capacity, entities with a limited activation capability shall also report the amount of FCR capacity which has limited activation capability. The maintained capacity which has limited activation capability is calculated by Equation (5.1) to (5.3).

For an FCR-N providing entity with a reservoir, the capacity is limited if the reservoir is drained or saturated (and cannot dispose of energy).

$$L_{\mathrm{FCR-N}} = \text{ limited if} \begin{cases} \mathrm{E_{reservoir\ max}} < \mathrm{E_{current\ reservoir}} + \\ + \left(\mathrm{P_{reservoir\ inflow}} - \mathrm{P_{setpoint}} + \mathbf{C_{pre-qual\ FCR-N}}\left(\mathrm{P_{setpoint}}\right)\right) * \mathrm{t_{req}} \\ \text{or} \\ \mathrm{E_{reservoir\ min}} > \mathrm{E_{current\ reservoir}} + \\ + \left(\mathrm{P_{reservoir\ inflow}} - \mathrm{P_{setpoint}} - \mathbf{C_{pre-qual\ FCR-N}}\left(\mathrm{P_{setpoint}}\right)\right) * \mathrm{t_{req}} \end{cases} \quad (5.4)$$

Endurance of FCR-N capacity with limited activation capability (the time until an entity providing FCR-N is limited) is calculated according to

$$\mathbf{L_{FCR-N\ endurance}} = \left| \frac{\boldsymbol{E}_{\mathbf{current\ reservoir}}}{\boldsymbol{P}_{\mathbf{setpoint}} - \boldsymbol{P}_{\mathbf{reservoir\ inflow}} + \boldsymbol{C}_{\mathbf{pre-qual\ FCR-N}}\left(\boldsymbol{P}_{\mathbf{setpoint}}\right)} \right| * \mathbf{60} \quad (5.5)$$

For FCR-D downwards, the capacity is limited if the upper limitation of the reservoir has been reached

$$\boldsymbol{L}_{\textbf{FCR-D down}} = \textbf{ limited if} \tag{5.6}$$

$$\boldsymbol{E}_{\textbf{reservoir max}} < \boldsymbol{E}_{\textbf{current reservoir}} + \left(\boldsymbol{P}_{\textbf{reservoir inflow}} - \boldsymbol{P}_{\textbf{setpoint}} + \boldsymbol{C}_{\boldsymbol{pre-qual\ FCR-D\ down}}(\boldsymbol{P}_{\textbf{setpoint}}) + \boldsymbol{C}_{\textbf{pre-qual FCR-N}}(\boldsymbol{P}_{\textbf{setpoint}})\right) * \boldsymbol{t}_{\textbf{req}}$$

Endurance of FCR-D downwards capacity with limited activation capability is calculated according to

$$\boldsymbol{L}_{\textbf{FCR-D down endurance}} = \frac{\left|\frac{\boldsymbol{E}_{\textbf{reservoir max}} - \boldsymbol{E}_{\textbf{current reservoir}}}{\boldsymbol{P}_{\textbf{reservoir inflow}} - \boldsymbol{P}_{\textbf{setpoint}} + \boldsymbol{C}_{\textbf{pre-qual FCR-D down}}(\boldsymbol{P}_{\textbf{setpoint}}) + \boldsymbol{C}_{\textbf{pre-qual FCR-N}}(\boldsymbol{P}_{\textbf{setpoint}})}\right|}{\textbf{60}} \tag{5.7}$$

For FCR-D upwards, the capacity is limited if the lower limitation of the reservoir has been reached

$$\boldsymbol{L}_{\textbf{FCR-D up}} = \textbf{ limited if} \tag{5.8}$$

$$\boldsymbol{E}_{\textbf{reservoir min}} > \boldsymbol{E}_{\textbf{current reservoir}} + \left(\boldsymbol{P}_{\textbf{reservoir inflow}} - \boldsymbol{P}_{\textbf{setpoint}} - \boldsymbol{C}_{\textbf{pre-qual FCR-D up}}(\boldsymbol{P}_{\textbf{setpoint}}) - \boldsymbol{C}_{\textbf{pre-qual FCR-N}}(\boldsymbol{P}_{\textbf{setpoint}})\right) * \boldsymbol{t}_{\textbf{req}}$$

Endurance of FCR-D downwards capacity with limited activation capability is calculated according to

$$\boldsymbol{L}_{\textbf{FCR-D up endurance}} = \frac{\left|\frac{\boldsymbol{E}_{\textbf{current reservoir}} - \boldsymbol{E}_{\textbf{reservoir min}}}{\boldsymbol{P}_{\textbf{setpoint}} + \boldsymbol{C}_{\textbf{pre-qual FCR-D up}}(\boldsymbol{P}_{\textbf{setpoint}}) + \boldsymbol{C}_{\textbf{pre-qual FCR-N}}(\boldsymbol{P}_{\textbf{setpoint}}) - \boldsymbol{P}_{\textbf{reservoir inflow}}}\right|}{\textbf{60}} \tag{5.9}$$

where
$E_{\text{reservoir max}}$ is the reservoir current maximum storage threshold/limit [MWh]
$E_{\text{reservoir min}}$ is the reservoir current minimum storage threshold/limit [MWh]
$E_{\text{current reservoir}}$ is the current reservoir level [MWh]

$P_{\text{reservoir inflow}}$ is the current reservoir inflow if applicable [MW]

$L_{\text{FCR-N endurance}}$ is the current endurance [minutes]

$L_{\text{FCR-D down endurance}}$ is the current endurance [minutes]

$L_{\text{FCR-D up endurance}}$ is the current endurance [minutes]

t_{req} is the required full activation capability time, to be specified by the TSO [h]

For FCR providing entities, limited due to other than reservoir restrictions, the calculations shall be performed in a similar fashion but with necessary modifications to the procedure.

5.4 Activated FCR capacity calculation

Activated FCR capacity, A_{FCR}, is to be calculated as

$$\boldsymbol{A}_{\mathbf{FCR}} = \boldsymbol{P}_{\mathbf{actual}} - \boldsymbol{P}_{\mathbf{setpoint}} - \boldsymbol{P}_{\mathbf{other\ reserves}} \quad (5.10)$$

where
P_{actual} is the current instantaneous active power
P_{setpoint} is the active power setpoint, corresponding to the output power at 50.00 Hz (including verified control errors)
$P_{\text{other reserves}}$ is the power output of other reserves than FCR not included in the setpoint

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Appendices

- **Appendix 1: Application document template**
- **Appendix 2: FCR-N test program template**
- **Appendix 3: FCR-N test Excel sheet**
- **Appendix 4: FCR-N test report template**
- **Appendix 5: FCR-D test program template**
- **Appendix 6: FCR-D test Excel sheet (to be provided later)**
- **Appendix 7: FCR-D test report template**
- **Appendix 8: Logged data delivery template**
- **Appendix 9: Example prequalification package (to be provided later)**
  - **Appendix 9.1 Application document**
  - **Appendix 9.2 FCR-N test report**
  - **Appendix 9.3 FCR-D test report**

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