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

27 January 2021

# Contents

## Definitions

| | |
|---|---|
| **Activated capacity** | Part of the active power output caused by FCR activation |
| **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 |
| **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 |
| **TSO** | Transmission System Operator |
| **Setpoint** | Part of the active power output that does not include FCR activation |

# 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.

The objective of the frequency containment reserves is to stabilise and maintain the frequency in case of imbalances. FCR is a fast power activation that activates automatically and proportionally in response to a deviation in frequency within certain intervals. FCR for normal operation (FCR-N) balances fluctuations between production and consumption in normal operation and FCR for disturbances (FCR-D) balances large power imbalances that may occur.

In this document abbreviations and terminologies used in the Main document and throughout this document are explained. In section 2 the process for prequalification is presented. The test procedure is presented in section 3. The application of the test results in evaluating requirements compliance, including the deriving of mathematical representations of the dynamic behaviour of FCR providing entities, is explained in Section 4 to provide a better understanding on how entity's dynamic behaviour is evaluated. FCR capacity calculation for real-time telemetry and data logging purposes is explained in Section 5.

# 2 The prequalification process

The prequalification process shall ensure that the FCR provider is capable of providing FCR in accordance with the requirements from the TSO. 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[1]. 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. The prequalification process is illustrated in Figure 1.

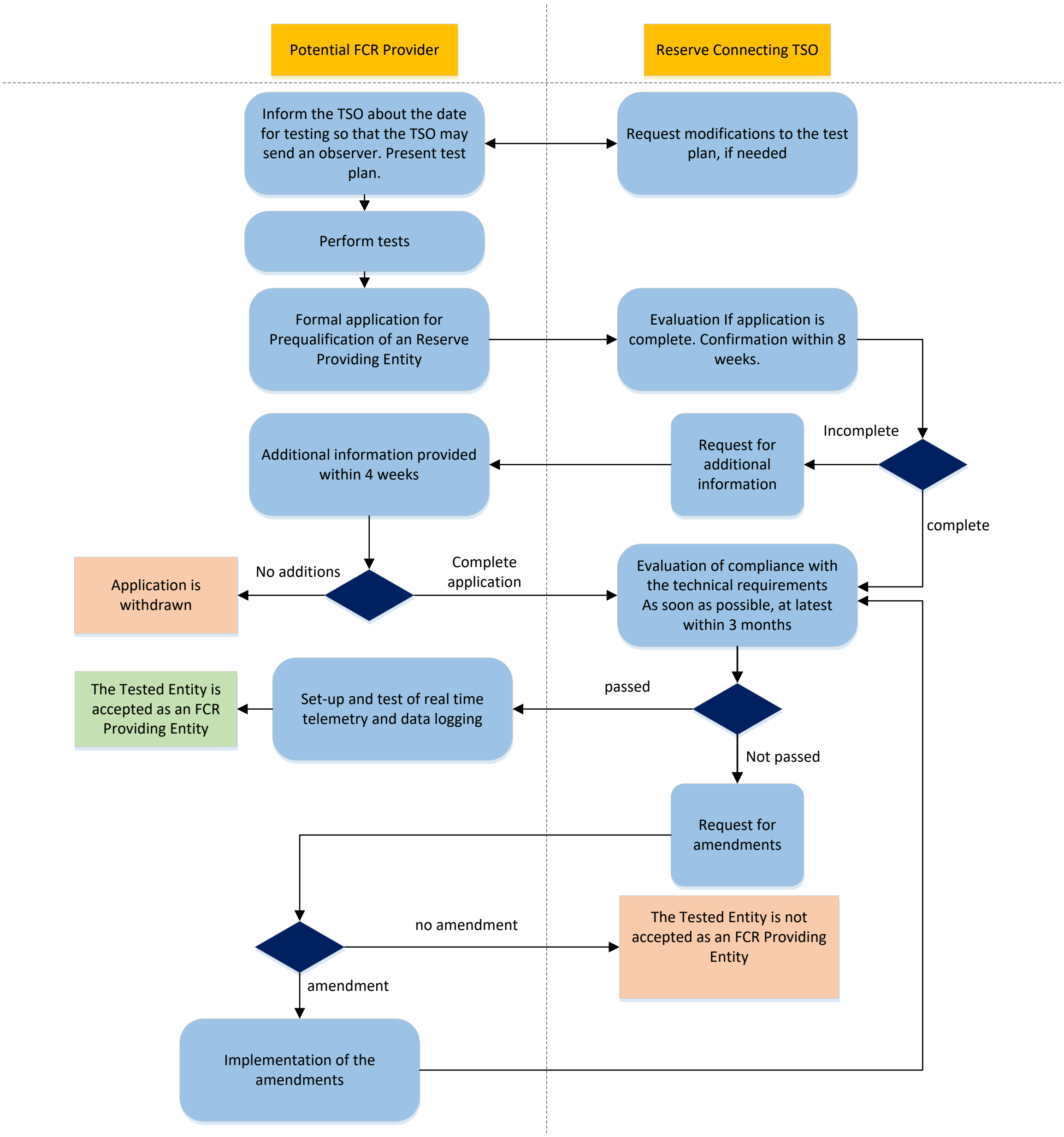



**Figure 1. Illustration of the steps in the prequalification process.**

[1] COMMISSION REGULATION (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation.

## 3 Test procedure

The FCR providing entity shall be synchronized to the grid during the test. The frequency control signal, normally from the measured grid frequency, is replaced by a synthetic signal as illustrated in Figure 2.

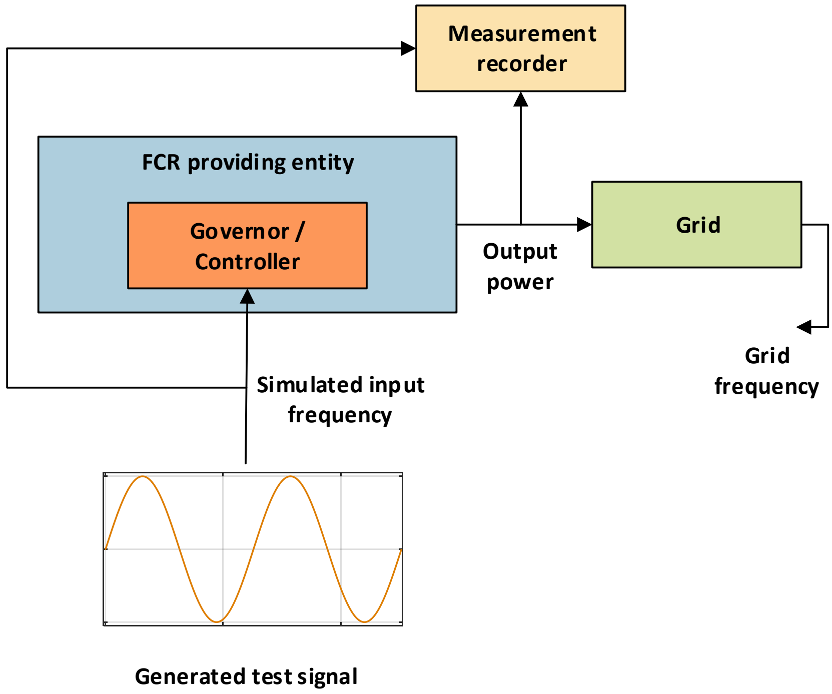



**Figure 2. Principle test setup.**

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. During testing, supplementary active power controls like aFRR shall be disabled so that the setpoint remains unchanged. Voltage control using frequency-voltage droop is allowed.

A test set is designed to highlight the properties associated with FCR provision;

- Steady state activation (stationary performance)
- Dynamic performance
- Dynamic stability
- Linearity

A single test set contains, not including special considerations or possible exemptions;

- FCR-N
  - 1 step response sequence
  - 7 sine responses
- FCR-D upwards
  - 1 step response sequence
  - 1 ramp response sequence
  - 5 sine responses
- FCR-D downwards

- 1 step response sequence
- 1 ramp response sequence
- 5 sine responses

Additional tests or considerations may be applicable depending on the FCR proving entities specific properties and test method. This includes

- Separate test for frequency measurement loop
- Linearity test for non-continuous responses
- FCR-D with separate high performance and high stability parameters
- Deactivation

The FCR properties depend on both ambient and operational conditions, such as loading level (power setpoint), droop settings, water level height (hydro), temperature of cooling water (thermal), and many more. All ambient and operational conditions cannot be tested, so the requirements aim to highlight those most important.

The FCR providing entities must confirm the compliance for the relevant operational ranges. Generally, it is required to complete one test set at a minimum of four operational conditions for both FCR-N and FCR-D upwards and downwards:

1) *Maximum active power setpoint* where the entity will provide FCR, and *maximum droop*, and corresponding controller parameter sets, where the entity will provide FCR.
2) *Maximum active power setpoint* where the entity will provide FCR, and *minimum droop*, and corresponding controller parameter sets, where the entity will provide FCR.
3) *Minimum active power setpoint* where the entity will provide FCR, and *maximum droop*, and corresponding controller parameter sets, where the entity will provide FCR.
4) *Minimum active power setpoint* where the entity will provide FCR, and *minimum droop*, and corresponding controller parameter sets, where the entity will provide FCR.

There are however exemptions given, listed below. Generally:

- If the entity is planned to deliver FCR at a single power setpoint, the tests 3) and 4) can be omitted.
- If the entity is planned to deliver FCR at a single droop setting, the tests 2) and 4) can be omitted.
- If a single parameter set is used for all power setpoints, sine testing at multiple power setpoints can be omitted. The power setpoint where stability is most challenging, normally the highest, shall be tested. E.g. hydro power using a single parameter set for entire power setpoint range is required to perform stability testing for high loading only.
- FCR-D providing entities can choose to perform tests for only FCR-D upwards or downwards, or both.

Subject to TSO approval prior to testing:

- For technologies where power setpoint does not influence the FCR provision capabilities, testing at a single power setpoint is sufficient for both steady state, dynamic performance and dynamic stability. E.g. batteries.
- Technologies can be given additional exemptions for testing requirements where compliance can be confirmed by the general knowledge of said technology, either from previous tests of similar units or other documentation.

It is the responsibility of the FCR providing unit owner to clarify uncertainties with regard to necessary tests.

Note also that some tests are equal for FCR-N and -D Upwards and Downwards. Results can therefore be reused for confirming compliance for one and the other, assuming the same parameter set is used.

## 3.1 FCR-N

### 3.1.1 FCR-N step tests

A step response sequence is used to determine steady state FCR-N capacity, backlash and performance. Synthetic step signals are injected in the frequency measurement loop, which gives a power response. The initial two steps, from 50.00 Hz to 49.95 Hz and back, are included to highlight the contribution of the backlash and similar non-linear effects. Each new step is injected after reaching steady state power response for a time sufficient enough to confirm steady state activation.

50.00 Hz → 49.95 → 50.00 → 50.10 → 50.00 → 49.90 → 50.00 Hz

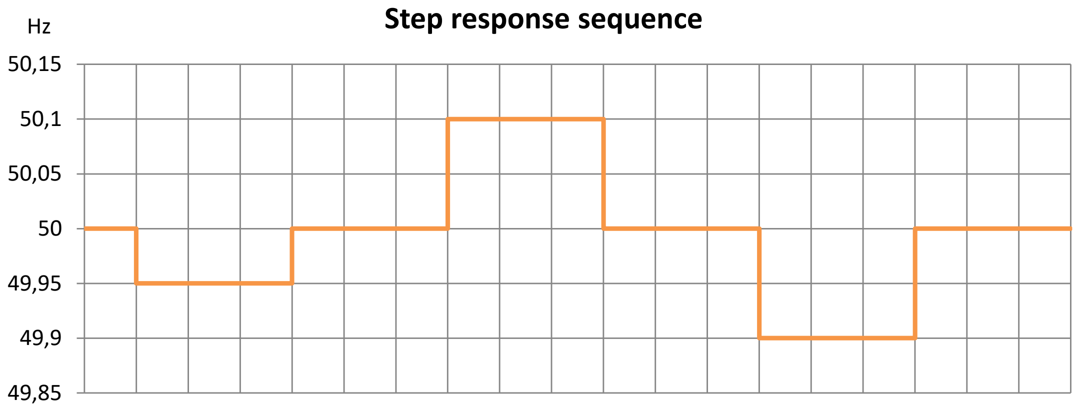



**Figure 3. Input frequency signal for FCR-N step response tests**

### 3.1.2 FCR-N sine tests

Sine tests are used to confirm stability and dynamic performance. Synthetic sinusoidal signals are injected in the frequency measurement loop, which gives a power response. For each time period, at least five periods shall be recorded after reaching a stable sinusoidal active power output.

The time periods for which to test is T = [10, 15, 25, 40, 50, 60, 70] seconds. The FCR provider may choose to perform tests at more time periods to investigate transfer function values in the area otherwise interpolated, see Subsection 4.1

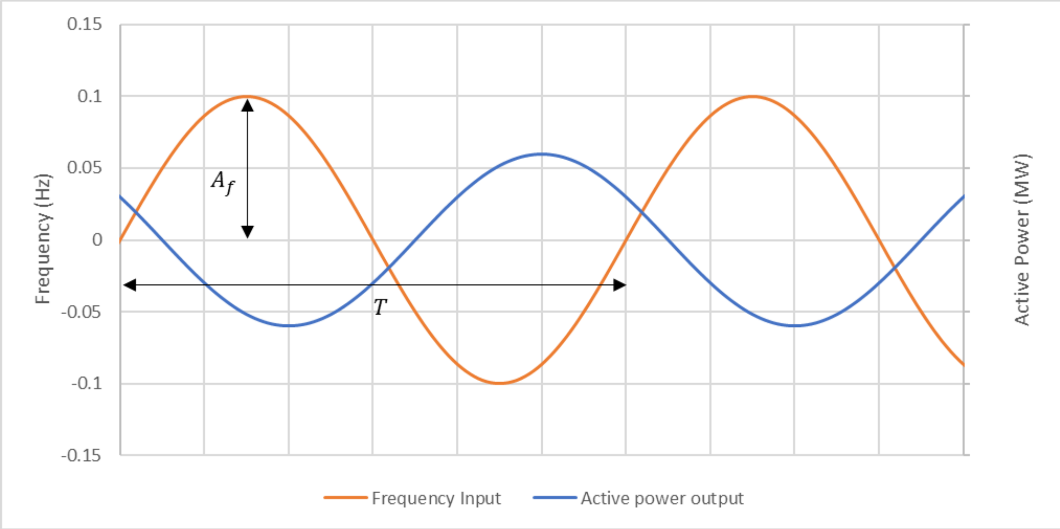



**Figure 4. Input frequency signal for FCR-N sine tests**

## 3.2 FCR-D upwards

### 3.2.1 FCR-D Upwards step tests

Step response sequences is performed to determine steady state FCR-D upwards capacity and confirm linear activation of FCR-D. The steps also provide necessary information about backlash and similar non-linear effects, and can be used for confirming correct switching of parameters between FCR-N and -D.

For FCR providing entities with switching of parameter sets between FCR-N and FCR-D, the initial step from 50.00 Hz to 49.50 Hz is used for compliance evaluation, and in that case FCR-N needs to be active. This switchover is only necessary to test (i.e. to keep FCR-N active) at a single power setpoint, but for both droop settings. The step sequence remains the same even if switchover testing is not performed.

50.00 Hz → 49.50 → 49.70 → 49.90 → 49.70 → 49.50 → 49.70 → 49.90

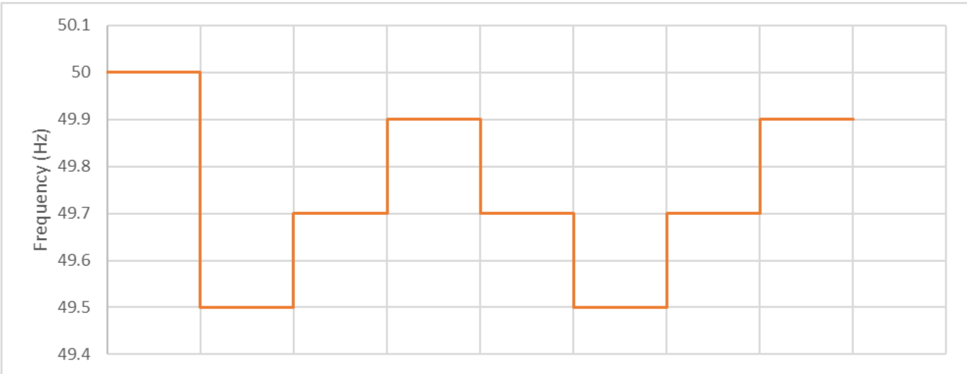



**Figure 5. Input frequency signal for FCR-D Upwards step response tests**

### 3.2.2 FCR-D Upwards ramp tests

Ramp tests are performed to assess the FCR-D performance. Synthetic steps and ramp signals are injected as frequency measurements, giving a power response. The initial two steps (50.00 → 49.80 Hz and 49.80 → 49.90 Hz for FCR-D upwards) are included to highlight the contribution of the backlash when injecting the ramp. The ramp should be at a rate of -0.24 Hz/sec.

50.00 Hz → 49.80 → 49.90 → 49.00→ 49.90


**Figure 6. Input frequency signal for FCR-D Upwards ramp response tests**

### 3.2.3 FCR-D Upwards sine tests

If the same parameter set is for FCR-D Upwards as for FCR-N, the test results from test in section 3.1.2 may be reused.

Sine tests are used to confirm stability. Synthetic sinusoidal frequency signals are injected, which produces a sinusoidal power response. While testing, the frequency input shall be an oscillation around 49.70 Hz (FCR-D upwards) with amplitude of 0,1 Hz. Alternatively, by the choice of the FCR provider, the test may be performed by a frequency input oscillating around 50,00 Hz whilst providing FCR-response continuously and symmetrically around 50,00 Hz, i.e. by deactivating deadbands/insensitivity used in control loop for FCR-D.

For each time period, at least five periods shall be recorded after reaching a stable sinusoidal active power output. The time periods for which to test is T = [10, 15, 25, 40, 50] seconds. The FCR provider may choose to perform tests at more time periods to investigate transfer function values in the area otherwise interpolated, see Subsection 4.1

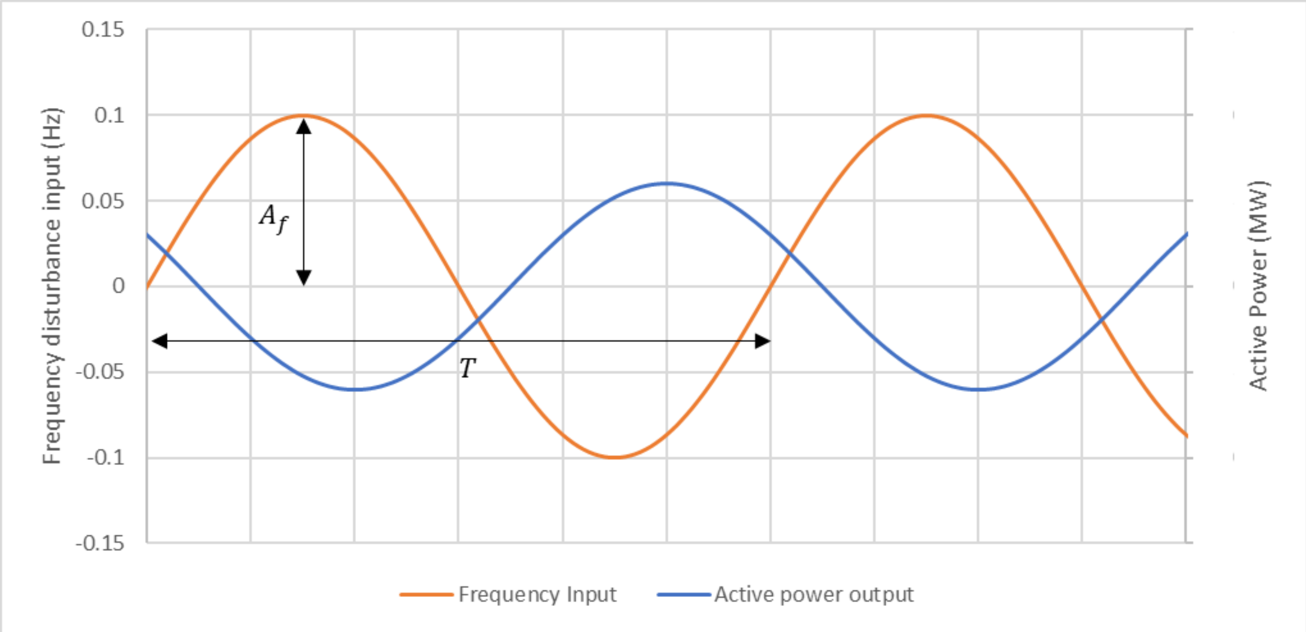



**Figure 7. Input frequency signal for FCR-D sine tests**

## 3.3 FCR-D downwards

### 3.3.1 FCR-D Downwards step tests

Step response sequences is performed to determine steady state FCR-D downwards capacity and confirm linear activation of FCR-D. The steps also provide necessary information about backlash and similar non-linear effects, and can be used for confirming correct switching of parameters between FCR-N and -D.

For FCR providing entities with switching of parameter sets between FCR-N and FCR-D, the initial step from 50.00 Hz to 50.50 Hz is used for compliance evaluation, and in that case FCR-N needs to be active. This switchover is only necessary to test (i.e. to keep FCR-N active) at a single power setpoint, but for both droop settings. The step sequence remains the same even if switchover testing is not performed.

50.00 Hz → 50.50 → 50.30 → 50.10 → 50.30 → 50.50 → 50.30 → 50.10

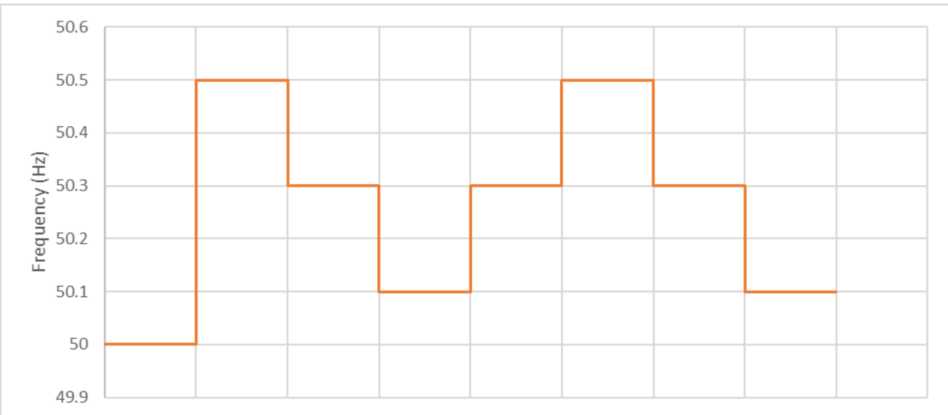



**Figure 8. Input frequency signal for FCR-D Downwards step response tests**

### 3.3.2 FCR-D Downwards ramp tests

Ramp tests are performed to assess the FCR-D performance. Synthetic steps and ramp signals are injected as frequency measurements, giving a power response. The initial two steps (50.00 → 50.20 Hz and 50.20 → 50.10 Hz) are included to highlight the contribution of the backlash when injecting the ramp. The ramp should be at a rate of 0.24 Hz/sec.

50.00 Hz → 50.20 → 50.10 → 51.00→ 50.10

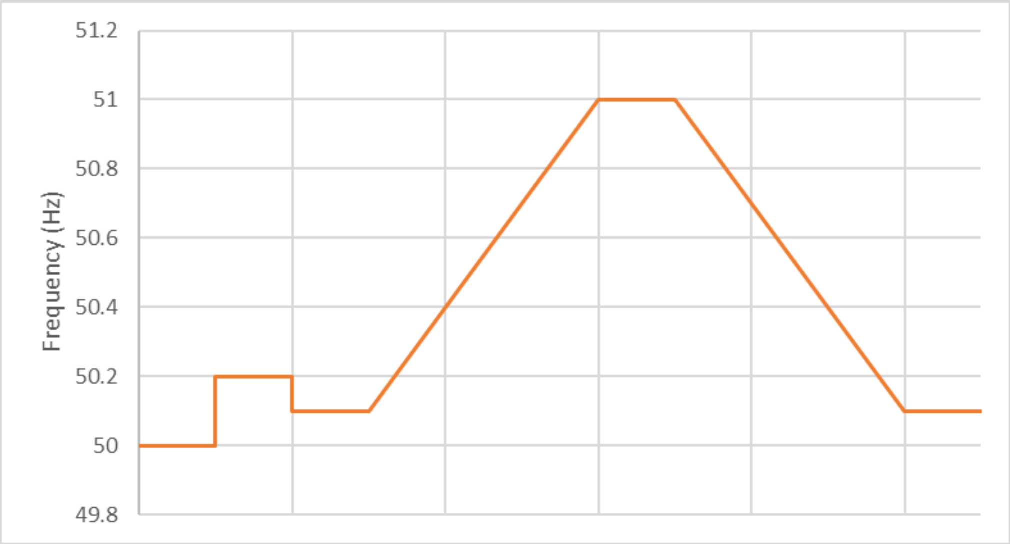



**Figure 9. Input frequency signal for FCR-D Downwards ramp response tests**

### 3.3.3 FCR-D Downwards sine tests

For a single controller parameter set is used for both FCR-D Upwards and Downwards, the test results from tests in section 3.2.3 may be reused. If the same parameter set is for FCR-D Downwards as for FCR-N, the test results from section 3.1.2 may be reused.

Sine tests are used to confirm stability. Synthetic sinusoidal frequency signals are injected, which produces a sinusoidal power response. While testing, the frequency input shall be an oscillation around 50.30 Hz with amplitude of 0,1 Hz. Alternatively, by the choice of the FCR provider, the test may be performed by a frequency input oscillating around 50,00 Hz whilst providing FCR-response continuously and symmetrically around 50,00 Hz, i.e. by deactivating deadbands/insensitivity used in control loop for FCR-D.

For each time period, at least five periods shall be recorded after reaching a stable sinusoidal active power output. The time periods for which to test is T = [10, 15, 25, 40, 50] seconds. The FCR provider may choose to perform tests at more time periods to investigate transfer function values in the area otherwise interpolated, see Subsection 4.1.

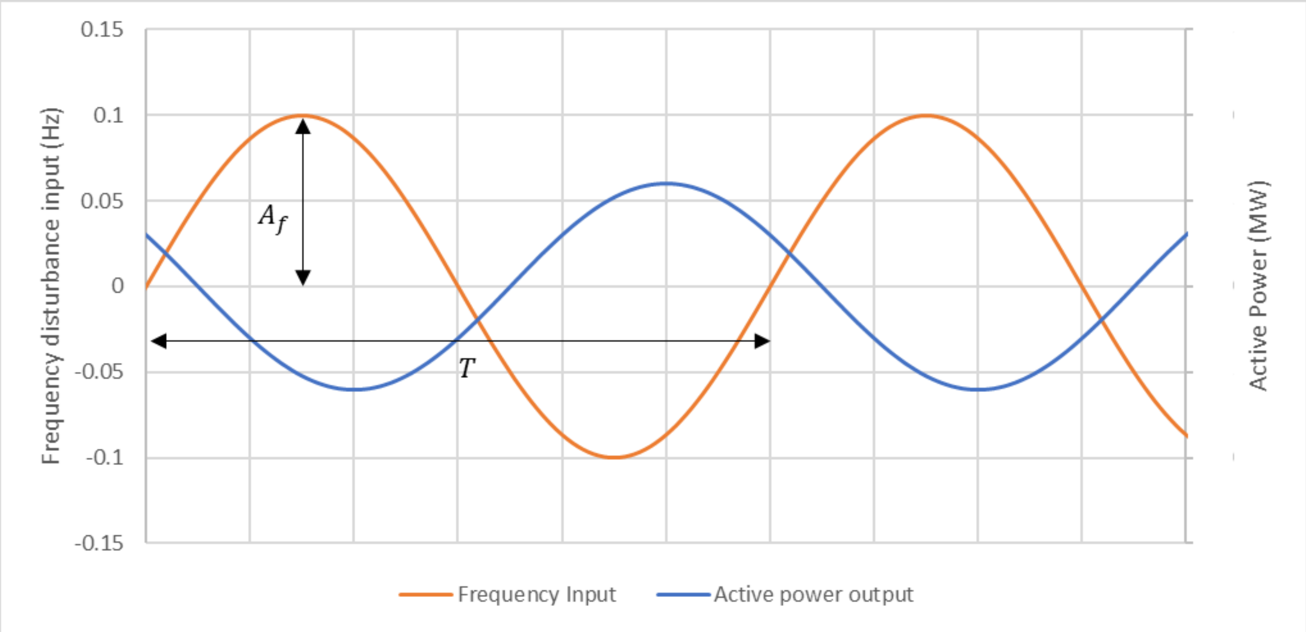



**Figure 10. Input frequency signal for FCR-D sine tests**

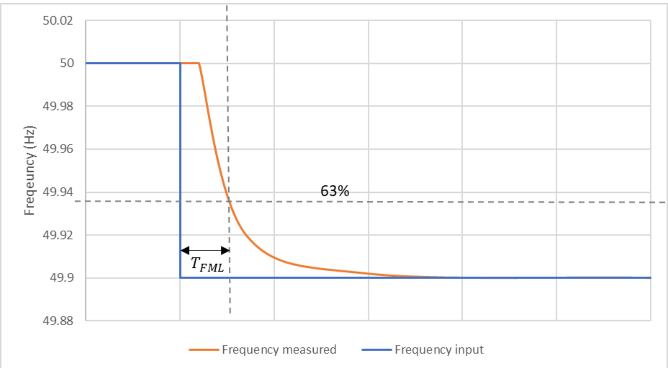
## 3.4 Special considerations

### 3.4.1 Separate test of frequency measurement loop

For providers choosing to use an internal software for generating the required test signals, i.e. steps, ramps and sinusoidal signals, the frequency measurement loop must be taken into account by including its properties. This is done by including a time delay, $T_{FML}$.

There are four options for determining the time delay

1. Separate test of the frequency measurement loop, by inserting an externally generated frequency step response to measure the time constant of the response.




2. Documentation from supplier of the equipment.
3. References to previously tests of equal equipment.
4. Using the default value provided by the TSOs[2], $T_{FML} = x$ second.

[2] The default value is purposefully set to a high value to ensure a margin.

### 3.4.2 Linearity test

For entities with a non-continuous response, a linearity test shall be performed to verify compliance with the requirement for linearity.

For FCR-N, the test consists of a sequence of ramps illustrated in Figure 11.

50.0 Hz → 49.9 Hz → 50.0 Hz → 50.1 Hz → 50.0 Hz

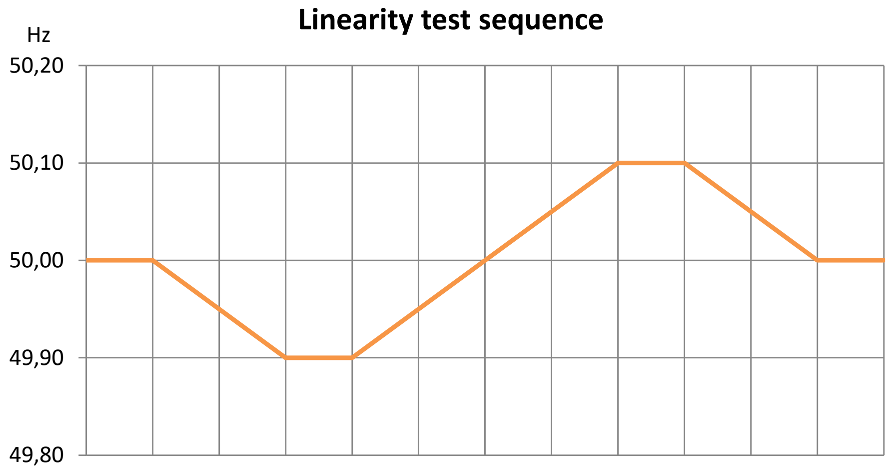



**Figure 11. FCR-N linearity test sequence to be performed for each setpoint and parameter set.**

I.e. both activation and deactivation shall be tested in the upwards and downwards direction respectively. The ramp rate shall be at least 0.5 mHz/s, i.e. a full activation from 50.0 Hz to 49.9 Hz shall be made within maximum 200 seconds. A faster ramp rate may be chosen, up to 2 mHz/s, i.e. 50 seconds for full activation.

For FCR-D Upwards the test consists of a ramp sequence:

49.9 Hz → 49.5 Hz → 49.9 Hz

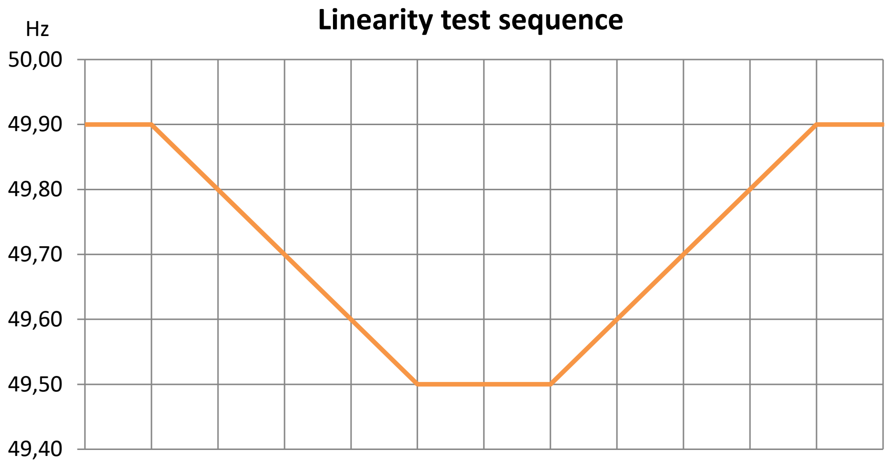



**Figure 12. FCR-D upwards linearity test sequence to be performed for each setpoint and parameter set.**

I.e. both activation and deactivation shall be tested in the upwards direction. The ramp rate shall be at least 2 mHz/s, i.e. a full activation from 49.9 Hz to 49.5 Hz shall be made within maximum 200 seconds. A faster ramp rate may be chosen, up to 8 mHz/s, i.e. 50 seconds for full activation.

For FCR-D Downwards the test consists of a ramp sequence:

50.1 Hz → 50.5 Hz → 50.1 Hz

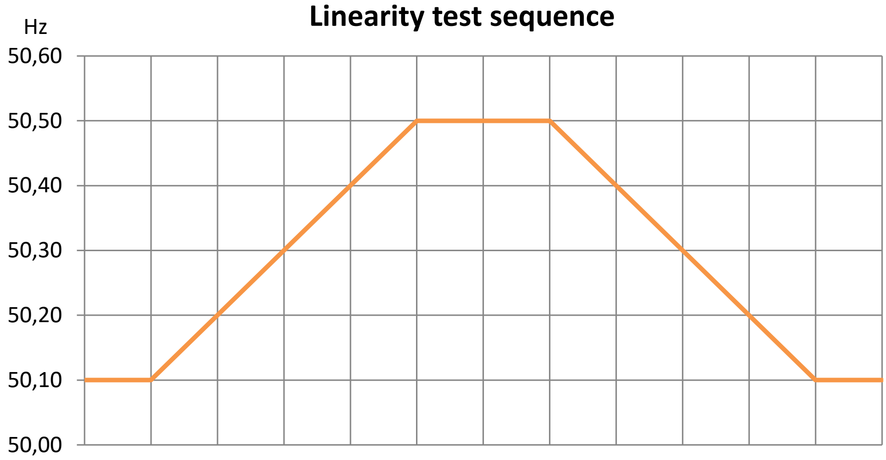



**Figure 13. FCR-D. downwards linearity test sequence to be performed for each setpoint and parameter set.**

I.e. both activation and deactivation shall be tested in the downwards direction. The ramp rate shall be at least 2 mHz/s, i.e. a full activation from 50.1 Hz to 50.5 Hz shall be made within maximum 200 seconds. A faster ramp rate may be chosen, up to 8 mHz/s, i.e. 50 seconds for full activation.

### 3.4.3 FCR-D with separate high performance and high stability parameters

Instead of using one set of FCR-D parameters that qualifies with all requirements, the provider may choose to use a combination of a *high performance* parameter set and a *high stability* parameter set. The high performance parameters are used to achieve good performance during a frequency disturbance. They are active for a limited time, after which the entity switches to the high stability parameters to ensure stable operation.

When using the high performance parameters, the entity is allowed to have a reduced stability margin, which in turn allows for a faster response. The stability margin, i.e. the radius of the stability margin circle around the Nyquist point, may be reduced maximally to a fourth of the general requirement when applying the high performance parameters. The high stability parameters set must comply with the general stability requirement and with the dynamic performance requirements for FCR-N, as described in the Main document.

Entities providing FCR-D with separate parameters for high performance and high stability shall perform separate sine testing for each parameter set separately, with parameter switching disabled.

### 3.4.4 Deactivation

FCR-D providing entities shall in general be able to deactivate their response symmetrically. The testing is then performed per the general instructions above, where deactivation is tested the same way as activation.

FCR-D providing entities utilising separate parameters for high performance and high stability, as outlined above, shall perform separate sine and step testing for each parameter set, with switching disabled. The ramp tests shall be performed per the general instructions, with parameter switching active.

Some FCR-D providing entities will be allowed to exist within a limited quota for entities with a grace period of 15 minutes where the deactivation requirement does not apply, as described in the Main document. Such entities will not be required to perform sine testing. When performing testing on such entities enough resting time shall be applied between each activation in the step and ramp sequences respectively, so that each activation is unhindered by previous activations and the grace period. The detailed testing arrangements for such entities must be agreed with the TSO.

# 4 Evaluation of compliance

This chapter provides detail on how the requirements should be understood, and how they are evaluated from the test results. The TSOs will provide the necessary IT-tools to automatically perform all calculations and evaluations of test results, and hence this information is provided for those who want to understand the inner workings of that tool, or to create tools of their own.

## 4.1 Deriving FCR-N and FCR-D transfer function values from testing

The requirements for stability and partially for performance is given by frequency domain criteria. Therefore, the frequency domain response, i.e. the transfer function, of FCR providing entities must be derived. Since not all frequencies are tested, the transfer function is derived by evaluation of tests at specific periods.

The frequency domain requirements are expressed and evaluated assuming linearity of the evaluated system, i.e. no mechanical deadbands/insensitivities/backlash[3]. Such non-linear characteristics may in reality be present in the FCR providing entities being tested. A method to account for these non-linearities is also presented in this section. The method is also applicable should the backlash be zero.

In short, the transfer function is derived by calculation using

- Step tests to evaluate backlash and stationary FCR activation
- Sine tests at varying period times to evaluate phase shifts and magnification (damping/amplification) between the injected frequency signal and the FCR response

### 4.1.1 Base values

To calculate the magnification and phase shift, it is necessary to determine what is the stationary active power step response and the backlash scaling factor to compensate for the non-linearity.

Using the test sequences outlined in Section 3 and shown in Figure 14, Figure 15 and Figure 16, the stationary active power step response from a 0.1 Hz step ($A_{step}$) is calculated, not including the contribution of the backlash. For FCR-D it is calculated for a 0.2 Hz step.

$$\Delta P_{Normalization} = \frac{|\Delta P_1| + |\Delta P_3|}{2}\ [MW] \tag{3.1}$$

[3] Backlash is used throughout this document as the general denotation of mechanical deadband/insensitivities/backlash.

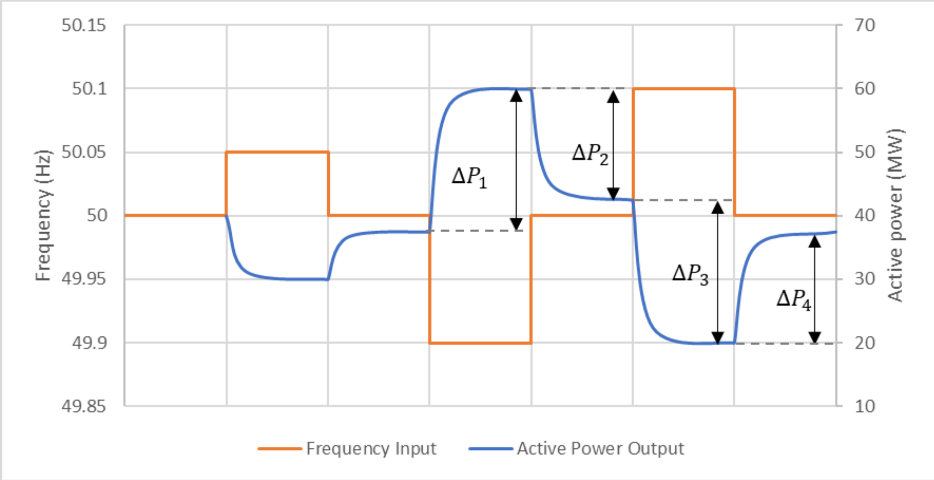



**Figure 14. Example response (blue) from input frequency (orange) according to FCR-N step test.**

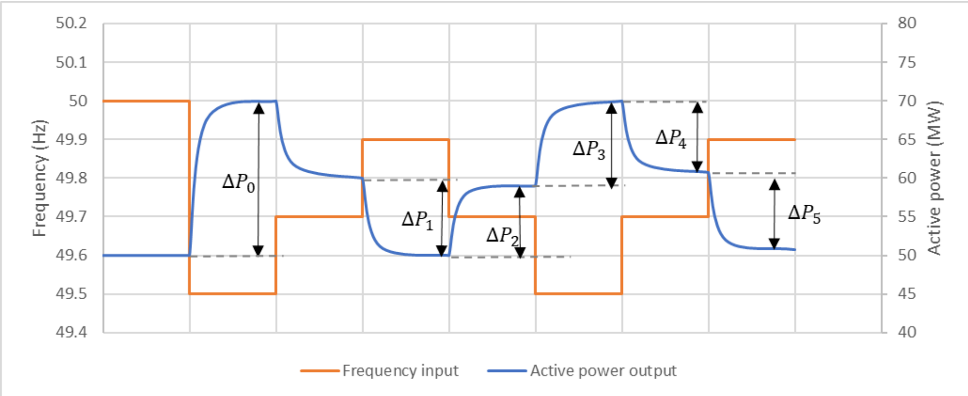



**Figure 15. Example response (blue) from input frequency (orange) according to FCR-D Upwards step test.**

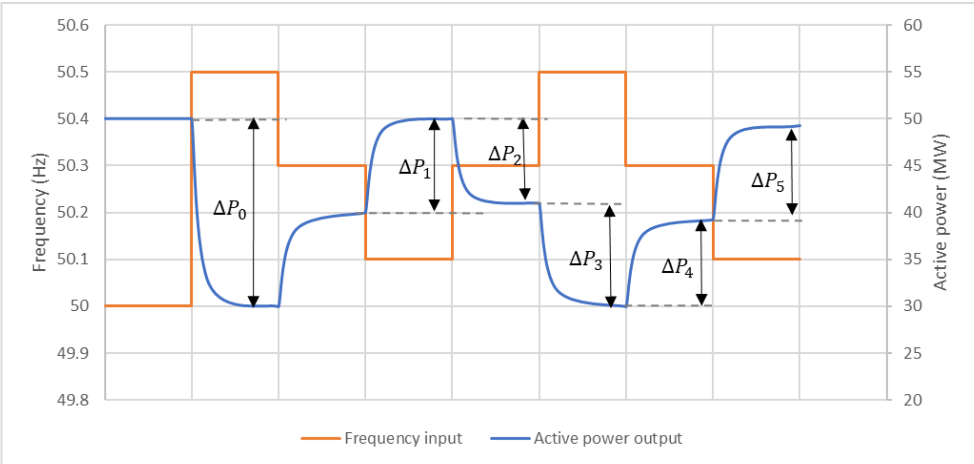



**Figure 16. Example response (blue) from input frequency (orange) according to FCR-D Downwards step test.**

To account for the backlash, $2D_{pu}$, the results are used to calculate the per unit value as

$$2D_{pu} = \frac{||\Delta P_1| - |\Delta P_2|| + ||\Delta P_3| - |\Delta P_4||}{2\ \Delta P_{Normalization}}\ [p.u.] \tag{3.2}$$

Based on the total backlash in per unit ($2D_{pu}$), a backlash scaling factor $h$ is obtained from Table 1[4].

**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 | | | | |

The backlash factor, and the normalization factor completes the calculation of the normalization factor, used to derive the gain and phase shifts of the sine tests,

$$e = \frac{h \cdot \Delta P_{Normalization}}{A_{\text{step}}} \tag{3.3}$$

### 4.1.2 Gain and phase shift

A transfer function value can be defined as

- The gain that describes the magnification of the output relative to the input signal, and;
- The time shift that describes the phase shift of the output relative to the input signal.

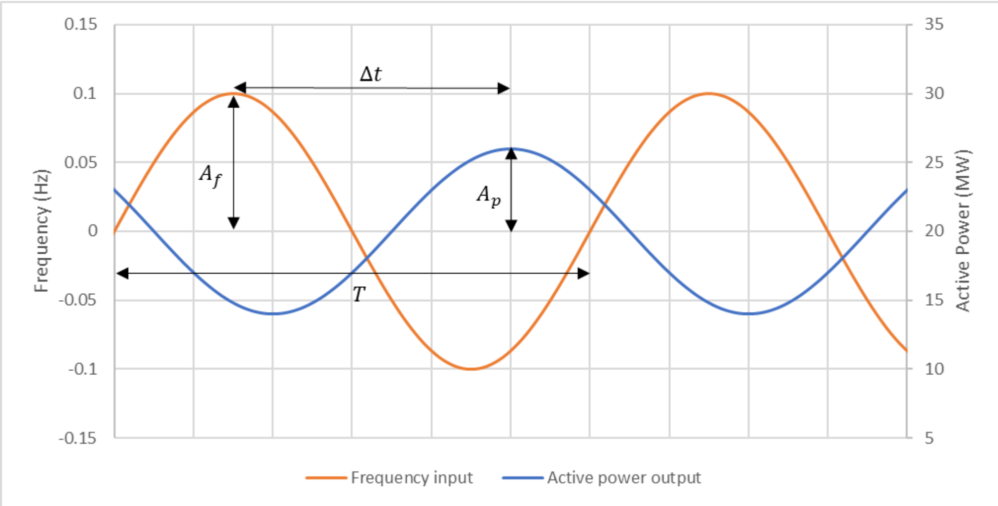



**Figure 17: Example response (blue) from input frequency (orange) for FCR sine test**

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

[4] The total backlash is not allowed to be above 0.3 p.u.

$$\omega = \frac{2\pi}{T} \tag{3.4}$$

The gain in per unit is calculated as

$$|\boldsymbol{F}(\boldsymbol{j}\omega)| = \frac{A_p}{e\,A_f} \tag{3.5}$$

Where $A_p$ is the amplitude of the power output (MW), $A_f$ is the amplitude of the frequency input, $h$ the backlash scaling factor (unitless) and $e$ is the normalization factor .

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

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

where $T$ is the time period (s)and $\Delta t$ is the time difference (s) of the input frequency signal and output power signal, as shown in Figure 17.

When evaluating compliance, the transfer function values of the FCR providing unit is used together with the transfer function values for the model of the power system, $G(s)$. Note that $G(s)$ is different between FCR-N and -D, and between stability and performance for FCR-N, due to different dimensioning inertia-levels and regulating strengths in the system. The gain and phase shift for the power system transfer function is calculated without use of measurements. Equations (3.7)and (3.8) show the transfer functions for FCR-N and -D respectively. The values used for stability and performance are provided in sections 0, 4.2.3, 4.3.4 and 4.4.4.

$$\boldsymbol{G}\,(\boldsymbol{s}) = -\frac{600\text{ MW}}{0.1\text{ Hz}} \frac{f_0}{S_{n,}} \frac{1}{2H\,\boldsymbol{s} + K_f * f_0}\ [\text{p.u.}] \tag{3.7}$$

$$\boldsymbol{G}\,(\boldsymbol{s}) = -\frac{1450\text{ MW}}{0.4\text{ Hz}} \frac{f_0}{S_n} \frac{1}{2H\,\boldsymbol{s} + K_f * f_0}\ [\text{p.u.}] \tag{3.8}$$

In addition, the transfer function values of the dimensioning disturbance profile for FCR-N performance, $D(s)$, is calculated for the tested period times. It is derived from the characteristics of the system imbalances/disturbances, expressed by the transfer function in equation (3.9), using a time constant of 70 seconds. Furthermore, the requirement function is scaled by a factor of 1.05 in order to account for measurement uncertainty.

$$|D(j\omega)| = \frac{1}{1.05}\left|\frac{1}{70j\omega + 1}\right| \Leftrightarrow \left|\frac{1}{D(j\omega)}\right| = |73.5\,j\omega + 1.05| \tag{3.9}$$

An example of the results after calculating gain and phase shift for each tested time period is given in Table 2, for FCR-N. Note that only the white cells are derived from testing, while all others are theoretical values, which are equal for every test. Table 3 shows the transfer function values based on testing in combination with the theoretically derived transfer function values for the power system transfer function.

**Table 2: Example values for calculation of transfer function values for FCR-N providing entity and for power system**

| Period time, $T$ (s) | $F(j\omega)$ | | $G_{min}(j\omega)$ (stability) | | $G_{avg}(j\omega)$ (performance) | |
|---|---|---|---|---|---|---|
| | $\lvert F(j\omega)\rvert$ | $\arg(F(j\omega))$ (degrees) | $\lvert G_{min}(j\omega)\rvert$ | $\arg(G_{min}(j\omega))$ (degrees) | $\lvert G_{avg}(j\omega)\rvert$ | $\arg(G_{avg}(j\omega))$ (degrees) |
| 10 | 0.1589 | 226.8047 | 1.9837 | 94.361 | 2.2856 | -84.9735 |
| 15 | 0.1541 | 260.8024 | 2.9648 | 96.5258 | 3.4121 | -82.4843 |
| 25 | 0.1465 | 293.3907 | 4.8856 | 100.7941 | 5.6023 | -77.5989 |
| 40 | 0.1432 | 312.5649 | 7.6115 | 106.9642 | 8.6576 | -70.6173 |
| 50 | 0.143 | 318.3829 | 9.2944 | 110.8723 | 10.5016 | -66.2615 |
| 60 | 0.1434 | 321.7435 | 10.8543 | 114.5874 | 12.1753 | -62.1783 |
| 70 | 0.1444 | 323.6845 | 12.2852 | 118.0947 | 13.6768 | -58.3803 |

Using the transfer function values, the results can be combined to evaluate compliance. The needed information is the real part, the imaginary part and the gain of the inverse of the sensitivity transfer function $\frac{1}{S(j\omega)}$ and the gain of closed loop transfer function values, $G(j\omega)S(j\omega)$.

**Table 3: Example values for calculation of transfer function values for compliance evaluation of FCR-N stability and FCR-N performance requirement**

| Period time, $T$ (s) | Real part of inverse of sensitivity transfer function, $Re\{1 - F(j\omega)G_{min}(j\omega)\}$ | Imaginary part of inverse of sensitivity transfer function, $Im\{1 - F(j\omega)G_{min}(j\omega)\}$ | Gain of the inverse sensitivity function $\lvert 1 - F(j\omega)G_{min}(j\omega)\rvert$ | Closed loop transfer function, $S(s)G(s) = \left\lvert \frac{G_{avg}(j\omega)}{1-F(j\omega)G_{avg}(j\omega)} \right\rvert$ |
|---|---|---|---|---|
| 10 | 0.7544 | 0.1977 | 0.7799 | 3.0521 |
| 15 | 0.5436 | 0.0213 | 0.544 | 7.189 |
| 25 | 0.4079 | -0.4022 | 0.5728 | 9.5778 |
| 40 | 0.4474 | -0.9393 | 1.0404 | 7.3948 |
| 50 | 0.5294 | -1.2426 | 1.3506 | 6.8767 |
| 60 | 0.6321 | -1.5129 | 1.6396 | 6.5859 |
| 70 | 0.7464 | -1.7555 | 1.9076 | 6.3935 |

Figure 18 illustrates the Nyquist-curve and Figure 19 the closed loop transfer function values in relation to the requirements.

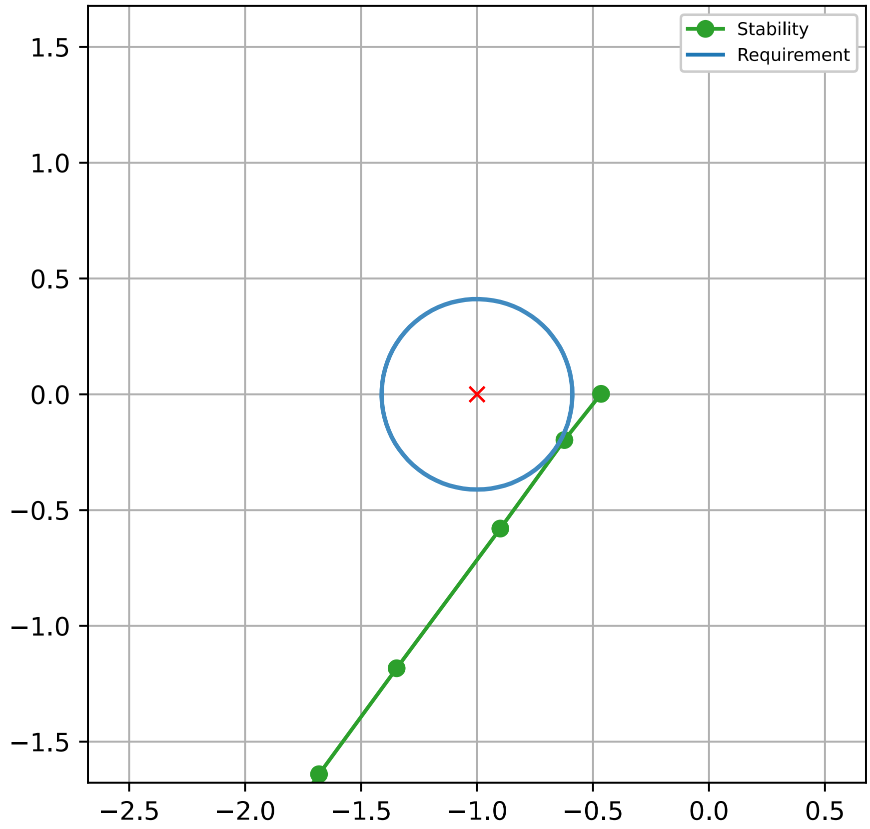



**Figure 18. Example response of transfer function values (green dots) and transfer function (green line) of the open loop response which qualifies for the stability margin requirement (blue circle) and does not enclose the point (-1,0) (red cross).**

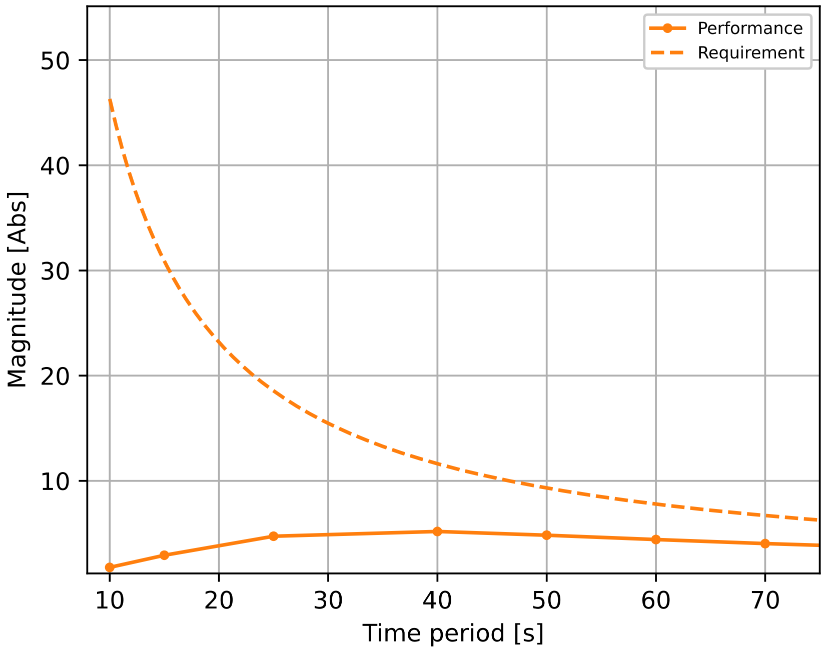



**Figure 19. Example response of transfer function values (orange dots), transfer function (orange solid line) of the closed loop response which qualifies for the performance requirement (orange dashed line).**

### 4.1.3 Frequency measurement loop

If tests are done using internal software in the governor for generating test signals, and thus not including the frequency measurement loop, this must be accounted for in calculating the transfer function.

The approximate frequency measurement loop impact, as determined by section 3.4.1, is included in the FCR providing units transfer function as a first order filter with a time constant $T_{FML}$, as shown in equation (3.10).

$$F(s) = \frac{1}{T_{FML}s + 1} F'(s) \tag{3.10}$$

Where $F'(s)$ is the transfer function not including the frequency measurement loop.

When calculating the transfer function values for the FCR providing unit, the transfer function values derived from sine testing is multiplied with transfer function values of the low pass filter for the respective time periods tested.

$$F(j\omega) = \frac{1}{T_{FML}j\omega + 1} F'(j\omega) \tag{3.11}$$

## 4.2 Evaluation of FCR-N requirements

### 4.2.1 Evaluation of FCR-N requirement for stationary activation

The capacity of an FCR-N providing entity is determined based on the step response sequence measurement outlined in Subsection 3.1.1 and examples of the response is shown in Figure 20.

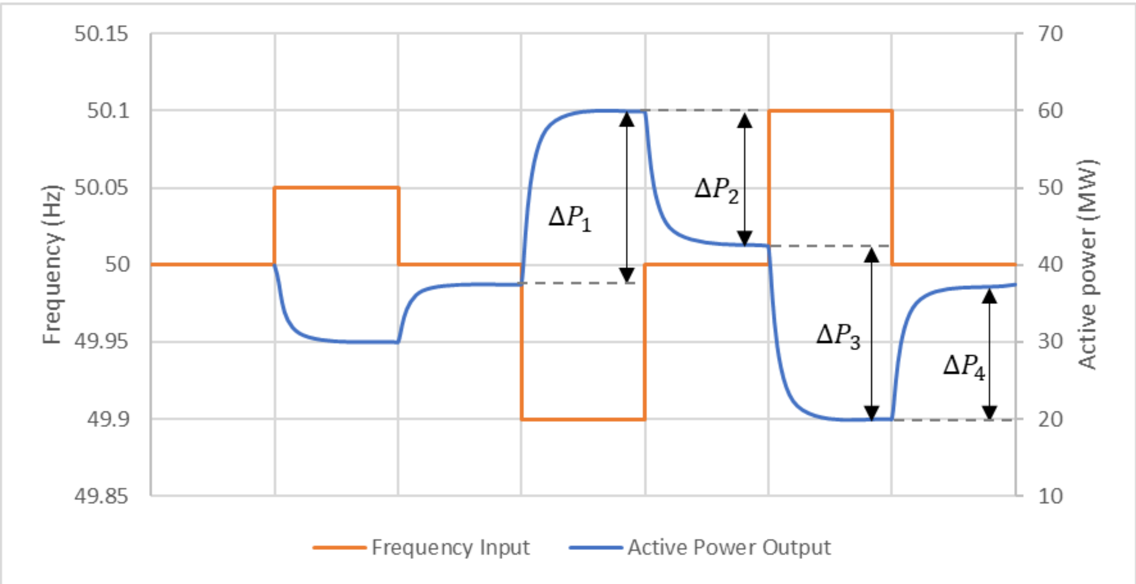



**Figure 20. Example response (blue) from input frequency (orange) according to FCR-N step test**

First, the total backlash is calculated as

$$\boldsymbol{2D} = \frac{||\Delta \boldsymbol{P_1}| - |\Delta \boldsymbol{P_2}|| + ||\Delta \boldsymbol{P_3}| - |\Delta \boldsymbol{P_4}||}{\boldsymbol{2}} \tag{3.12}$$

and the resulting FCR-N stationary capacity is, assuming compliance with performance and stability

$$\boldsymbol{C_{\text{FCR-N}}} = \frac{|\Delta \boldsymbol{P_1}| + |\Delta \boldsymbol{P_3}| - \boldsymbol{2D}}{\boldsymbol{2}} \tag{3.13}$$

For linear response upwards and downwards is confirmed by comparing the steps in each direction

$$\frac{\left||\Delta \boldsymbol{P_1}| - |\Delta \boldsymbol{P_3}|\right|}{\boldsymbol{C_{FCR-N}}} < \boldsymbol{0.1} \tag{3.14}$$

### 4.2.2 Evaluation of FCR-N requirement for dynamic performance

The dynamic performance requirements are confirming that the stationary capacity is activated correctly. For the steps from illustrated in Figure 20, following three requirements shall be fulfilled for all four steps:

1. $\Delta P_{60\text{s}} \geq 0.63 * \Delta P_x$
2. $\Delta P_{180\text{s}} \geq 0.95 * \Delta P_x$
3. $E_{\text{supplied}} \geq 24\, pu * s$

In the equations above;

$\Delta P_{60/180\text{s}}$ is the activated power in 60/180 seconds after applying the step signal

$\Delta P_{\text{x}}$ is the steady state FCR-N activation, i.e. the value where the power stabilizes, of the steps in the test illustrated in Figure 20 which is testes, $\Delta P_1, \Delta P_2, \Delta P_3$ *and* $\Delta P_4$.

$E_{\text{supplied}}$ is the activated energy 60 seconds after applying the step signal

$$E_{\text{supplied}} = \int_{t_{step}}^{t_{step}+60s} \Delta P(t) dt \tag{3.15}$$

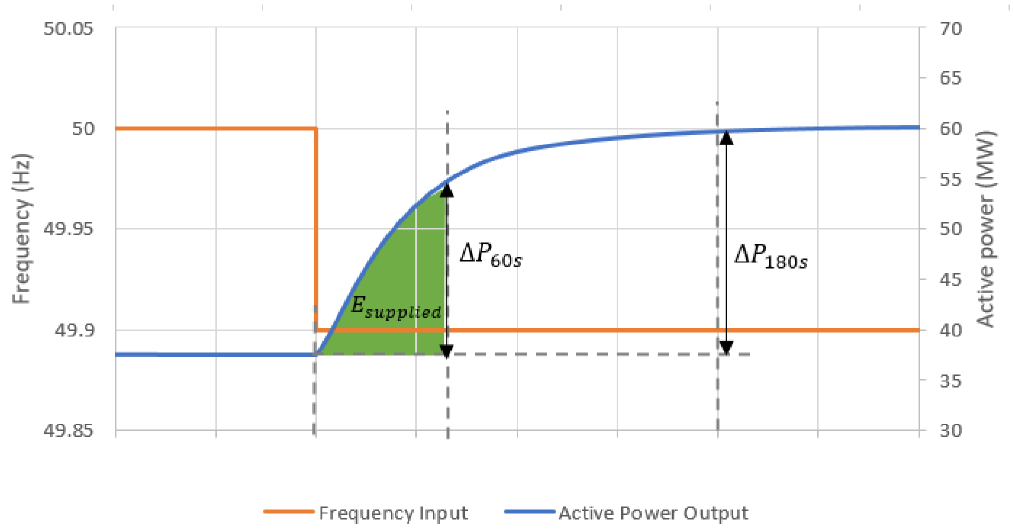



**Figure 21. Example response of a single step, blue, from input frequency, orange, according to FCR-N step test from 50 to 49.9 Hz**

Compliance with the FCR-N dynamic performance requirement is also evaluated in frequency domain by comparing the FCR providing entities response with the required system response. $F(s)$ is the transfer function of the FCR providing entity, derived as described in Subsection 4.1. Note that the requirement applies also to the interpolated values between the tested period times. The performance requirement is

$$\left|\frac{\mathrm{G_{avg}(s)}}{1-\mathrm{F}(s)\mathrm{G_{avg}(s)}}\right| < \left|\frac{1}{D(s)}\right| \tag{3.16}$$

Where s is the Laplace operator and $\mathbf{F(s)}$ is in per unit. And

$$G(s) = -\frac{600\text{ MW}}{0.1\text{ Hz}}\frac{f_0}{S_{\text{n,avg}}}\frac{1}{2H_{\text{avg}}s+K_{\text{f,avg}}*f_0} = -\frac{13.04}{9.048\,\mathbf{s}+0.5} \tag{3.17}$$

$$\left|\frac{1}{D(j\omega)}\right| = |73.5\,s + 1.05| \tag{3.18}$$

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

$K_{\text{f,avg}}$ is 0.01 (the load frequency dependence)

The compliance evaluation can be visualized as Figure 22. Other visualisations may also add value for providers evaluating the FCR proving entity during analyses or tuning. See appendices for details.

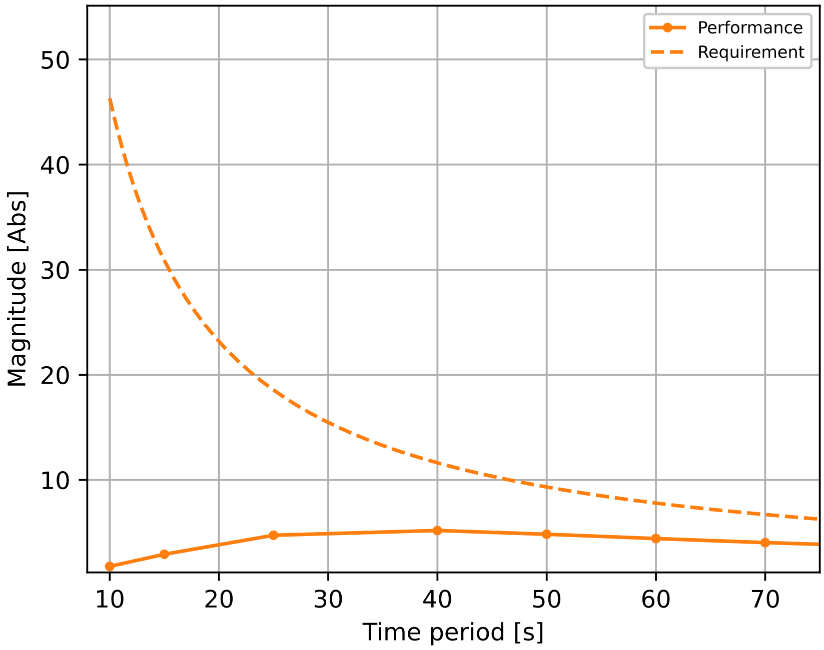



**Figure 22. FCR-N dynamic performance requirement (dashed) together with an example response (solid).**

### 4.2.3 Evaluation of FCR-N requirement for dynamic stability

The dynamic stability requirements are confirming that the response of the FCR provision is contributing correctly to damp frequency oscillations in the system.

Compliance with the FCR-N dynamic stability requirement is evaluated using the Nyquist-criteria for the open loop transfer function, given by equations (3.19) and (3.20). $F(s)$ is the transfer function of the FCR providing entity, derived as described in section in Subsection 4.1. Note that the requirement applies also to the interpolated values between the tested period times.

$$|1 - \mathrm{F}(s)\mathrm{G}_{\mathrm{min}}(\mathrm{s})| < \left|\frac{1}{M_s}\right| \tag{3.19}$$

$$Re\{1 - \mathrm{F}(s)\mathrm{G}_{\mathrm{min}}(\mathrm{s})\} > -1 \ \text{ when } \ Im\{1 - \mathrm{F}(s)\mathrm{G}_{\mathrm{min}}(\mathrm{s})\} = 0 \tag{3.20}$$

Where,

$$G_{min}(s) = -\frac{600\text{ MW}}{0.1\text{ Hz}}\frac{f_0}{S_{\mathrm{n,min}}}\frac{1}{2H_{\mathrm{min}}s+K_{\mathrm{f,min}}*f_0} = -\frac{13.04}{10.43\ s+0.25}\ [\text{p.u.}] \tag{3.21}$$

and,

$M_s$ is 2.31

s is the Laplace operator, $\omega = \frac{2\pi}{T}$, and T is the tested period time.

$f_0$ is 50 Hz
$S_{\mathrm{n,min}}$ is 23 000 MW

$H_{\text{min}}$ is $\frac{120\,000\ \text{MWs}}{S_{\text{n,min}}}$

$K_{f,\text{min}}$ is 0.005 (the load frequency dependence)

$F(s)$ given in per unit.

The Nyquist-diagram can be visualized as in Figure 23, also shown in the Main document. The graphical representation of the stability criteria, is that the Nyquist-curve created by the transfer function values and the interpolation between them, should not enclose the point (-1,0) and should not pass inside the stability margin circle.

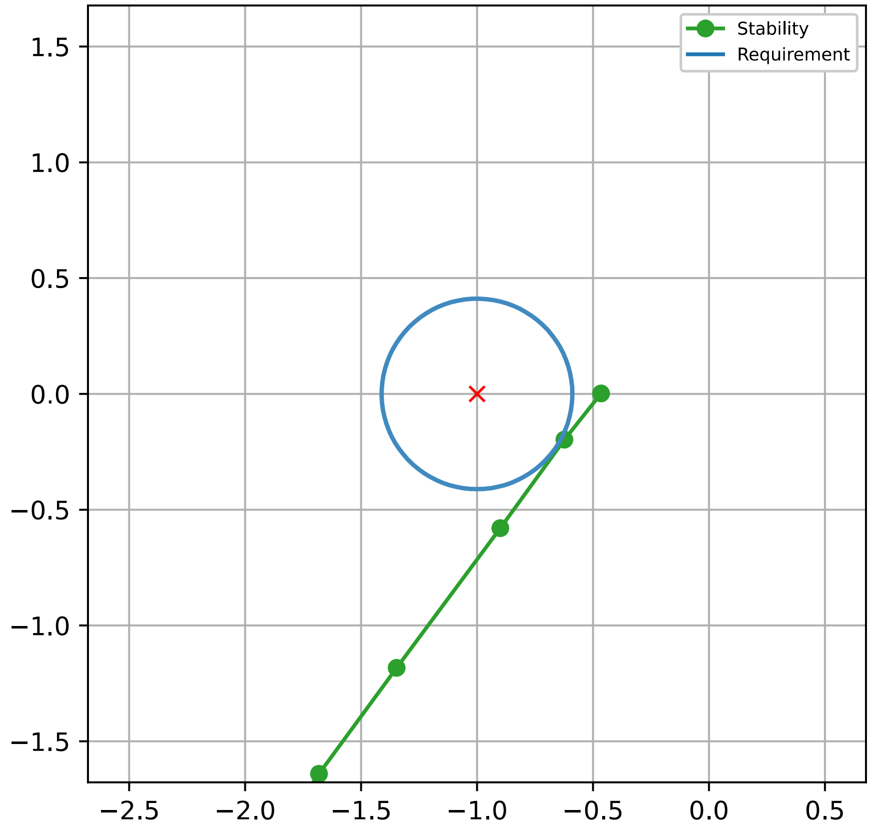



**Figure 23. Nyquist diagram of the Nyquist-point (-1,0), FCR-N stability margin requirement (blue) together with an example response (green).**

## 4.3 Evaluation of FCR-D Upwards requirements

### 4.3.1 Evaluation of FCR-D Upwards requirements for stationary activation

The capacity of an FCR-D Upwards providing entity is determined based on the step response sequence measurement outlined 3.2.1 and shown in Figure 24.

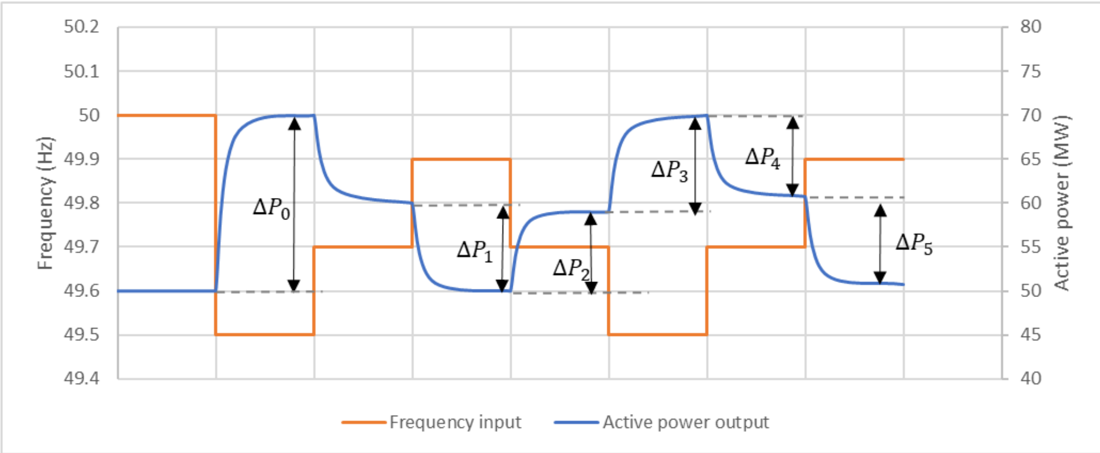



**Figure 24. Example response (blue) from input frequency (orange) according to FCR-D Upwards step test**

The FCR-D Upwards steady-state activation can be calculated as

$$\Delta \boldsymbol{P}_{\mathbf{ss,upwards}} = |\Delta \boldsymbol{P}_2 + \Delta \boldsymbol{P}_3| \qquad (3.22)$$

Linear response for activation and deactivation is confirmed by comparing the steps in each direction

$$\frac{\left||\Delta \boldsymbol{P}_2 + \Delta \boldsymbol{P}_3| - |\Delta \boldsymbol{P}_4 + \Delta \boldsymbol{P}_5|\right|}{\Delta \boldsymbol{P}_{\mathbf{ss,upwards}}} < \mathbf{0.1} \qquad (3.23)$$

## 4.3.2 Evaluation of FCR-D Upwards requirements for dynamic performance

The FCR-D dynamic performance is evaluated using the ramp tests, section 3.2.2. The entity is subjected to a frequency input ramp from 49.9 Hz to 49.0 Hz with a slope of -0.24 Hz/s for FCR-D upwards.

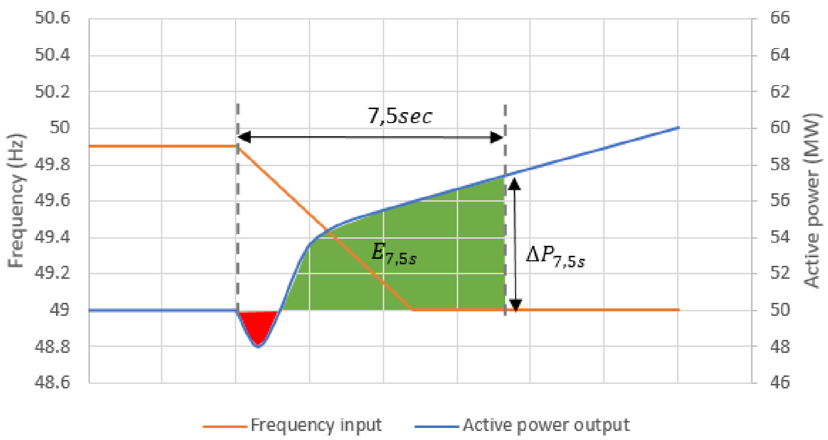



**Figure 25: Example response (blue) from input frequency (orange) according to ramp test sequence for evaluation of FCR-D upwards performance**

Using the values as illustrated in Figure 25, the following requirements shall be fulfilled for the ramp response:

1. $\Delta P_{7,5s} \geq 0.93 \cdot \Delta P_{ss}$ (MW)
2. $E_{7,5s} \geq 3.7 \cdot \Delta P_{ss}$ (MWs)

where

$\Delta P_{7,5s}$ is the activated power 7,5 seconds after the start of the ramp

$\Delta P_{ss}$ is the steady state FCR-D activation calculated in section 4.3.1.

$E_{7,5s}$ is the activated energy from the start of the ramp to 7,5 seconds after the start of the ramp, that is

$$E_{7,5s} = \left| \int_{t}^{t+7,5s} \Delta P(t) dt \right| \tag{3.24}$$

If the FCR providing entity does not fulfil the performance requirement, it can still provide the partial compliant provision. I.e., the FCR-D Upwards capacity, $C_{\text{FCR-D Upwards}}$, is minimum of the three requirements for stationary performance, power activation performance and energy supplement performance.

$$C_{\text{FCR-D Upwards}} = \mathbf{min}\left(\frac{\Delta P_{7.5s}}{0.93}, \Delta P_{\text{ss,upwards}}, \frac{E_{7,5s}}{3.7s}\right) \tag{3.25}$$

### 4.3.3 Evaluation of FCR-D Upwards requirements for dynamic performance for deactivation

TBD

### 4.3.4 Evaluation of FCR-D Upwards requirements for dynamic stability

The dynamic stability requirements are confirming that the response of the FCR-D Upwards provision is contributing correctly to damp frequency oscillations in the system.

Compliance with the FCR-D dynamic stability requirement is evaluated using the Nyquist-criteria for the open loop transfer function, given by equations (3.26) and (3.27). $F(s)$ is the transfer function of the FCR providing entity, as described in section 4.1. Note that the requirement applies also to the interpolated values between the tested period times.

$$|1 - \mathrm{F(s)G}_{min}(\mathrm{s})| < \left|\frac{1}{M_s}\right| \tag{3.26}$$

$$Re\{1 - \mathrm{F(s)G_{min}(s)}\} > -1 \text{ when } Im\{1 - \mathrm{F(s)G_{min}(s)}\} = 0 \tag{3.27}$$

Where

$$G_{min}(s) = -\frac{\Delta P_{ss,upwards}}{C_{FCR-D,Upwards}} \frac{1450\text{ MW}}{0.4\text{ Hz}} \frac{f_0}{S_{\text{n,min}}} \frac{1}{2H_{\text{min}}s + K_{\text{f,min}} * f_0} = -\frac{\Delta P_{ss,upwards}}{C_{FCR-D,upwards}} \frac{7.88}{10.43\,s + 0.25} \text{ [p.u.]} \tag{3.28}$$

And,

$M_s$ is 2.31

$s$ is the Laplace operator

$f_0$ is 50 Hz
where
$S_{\text{n,min}}$ is 23 000 MW
$H_{\text{min}}$ is $\frac{120\,000\ \text{MWs}}{S_{\text{n,min}}}$
$K_{f,\text{min}}$ is 0.005 (the load frequency dependence)

$\mathrm{F}(s)$ is given in per unit.

Compared to stability evaluation for FCR-N, the factor $\frac{\Delta P_{ss}}{C_{FCR-D,Upwards}}$ is included to account for possible performance scaling, and is applicable in cases where the FCR providing unit is unable to fully comply with the performance criteria, but is allowed to sell the part of the stationary capacity under the precondition that it is accounted for in the stability evaluation.

The Nyquist-diagram can be visualized as in Figure 26. The graphical representation of the stability criteria, is that the Nyquist-curve created by the transfer function values and the interpolation between them, should not enclose the point (-1,0) and should not pass inside the stability margin circle.

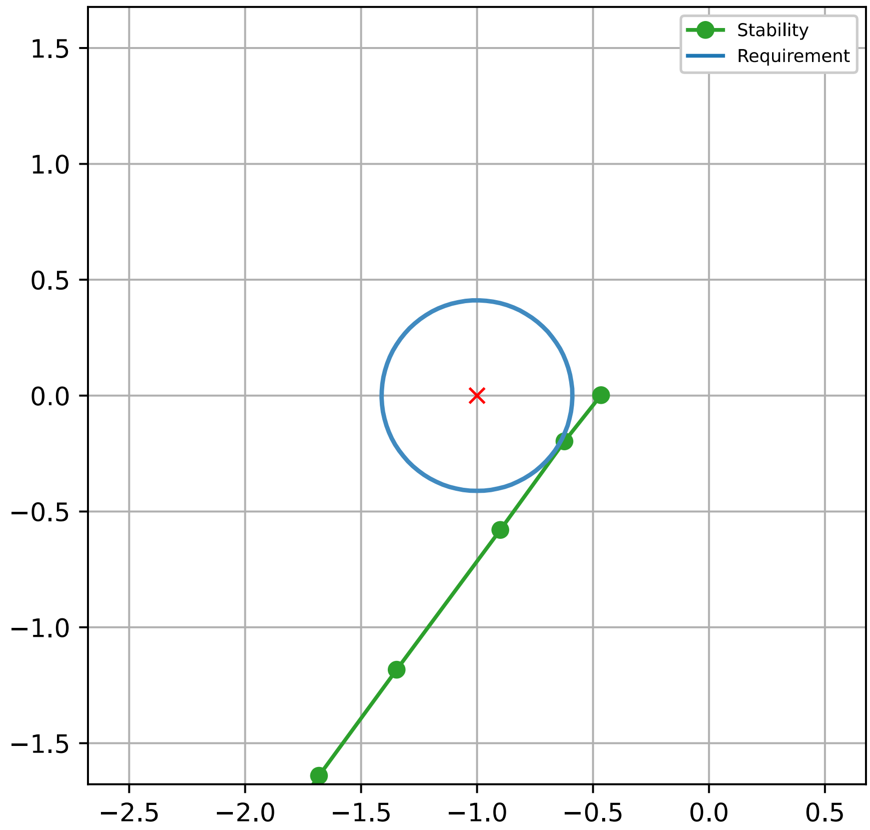



**Figure 26: FCR-N stability requirement (blue) together with an example response (green).**

## 4.4 Evaluation of FCR-D Downwards requirements

### 4.4.1 Evaluation of FCR-D Downwards requirements for stationary activation

The capacity of an FCR-N providing entity is determined based on the step response sequence measurement outlined in Subsection 3.3.1 and shown in Figure 27

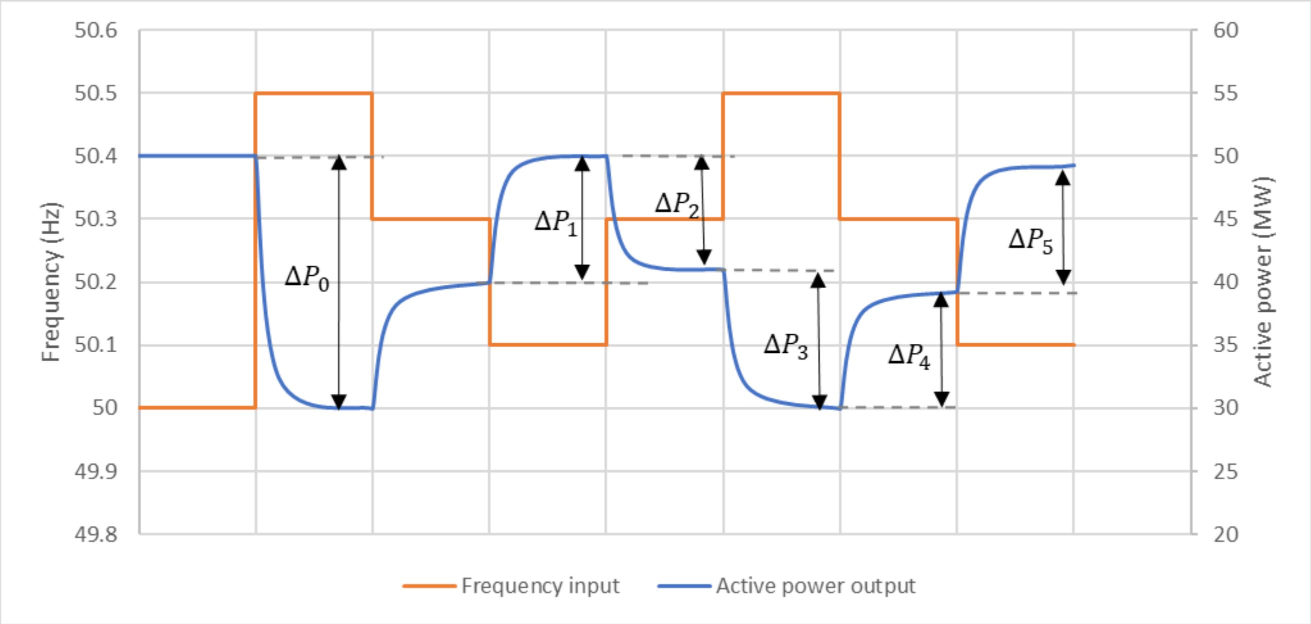



**Figure 27. Example response (blue) from input frequency (orange) according to FCR-D Downwards step test**

The FCR-D Downwards steady-state activation can be calculated using

$$\Delta \boldsymbol{P}_{\text{ss,downwards}} = |\Delta \boldsymbol{P}_2 + \Delta \boldsymbol{P}_3| \tag{3.29}$$

Linear response for activation and deactivation is confirmed by comparing the steps in each direction

$$\frac{\big||\Delta \boldsymbol{P}_2 + \Delta \boldsymbol{P}_3| - |\Delta \boldsymbol{P}_4 + \Delta \boldsymbol{P}_5|\big|}{\Delta \boldsymbol{P}_{\text{ss,downwards}}} < \mathbf{0.1} \tag{3.30}$$

### 4.4.2 Evaluation of FCR-D Downwards requirements for dynamic performance

The FCR-D dynamic performance is evaluated using the ramp tests, section 3.3.2. The entity is subjected to a frequency input ramp from 50.1 Hz to 51.0 Hz with a slope of 0.24 Hz/s.

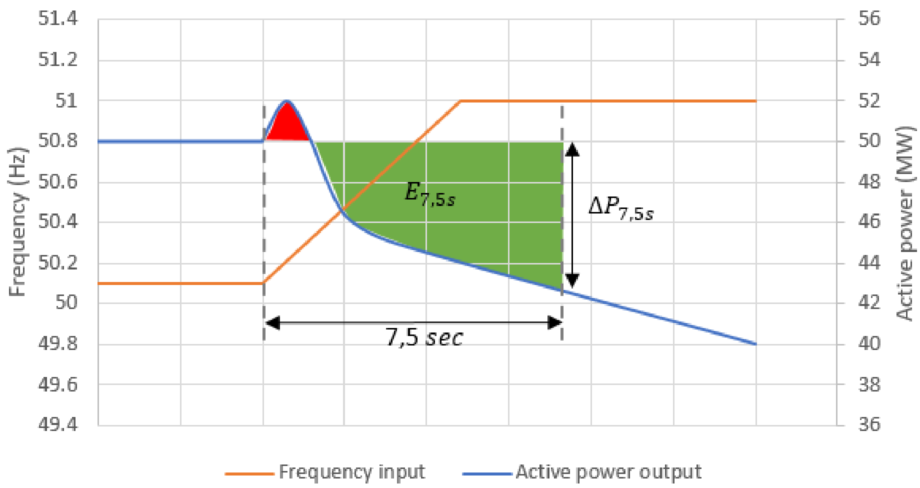



**Figure 28: Example response (blue) from input frequency (orange) according to ramp test sequence for evaluation of FCR-D downwards performance**

Using Figure 28 the following requirements shall be fulfilled for the ramp response:

1. $\Delta P_{7,5s} \geq 0.93 \cdot \Delta P_{ss}$ (MW)
2. $E_{7,5s} \geq 3.7 \cdot \Delta P_{ss}$ (MWs)

where

$\Delta P_{7,5s}$ is the activated power 7,5 seconds after the start of the ramp

$\Delta P_{ss}$ is the steady state FCR-D activation calculated in section 4.4.1.

$E_{7,5s}$ is the activated energy from the start of the ramp to 7,5 seconds after the start of the ramp, that is

$$E_{7,5s} = \int_t^{t+7,5s} \Delta P(t)dt \qquad (3.31)$$

If the FCR providing entity does not fulfil the performance requirement, it can still provide the partial compliant provision. I.e., the FCR-D Downwards capacity, $C_{\mathrm{FCR-D,downwards}}$, is minimum of the three requirements for stationary performance, power activation performance and energy supplement performance.

$$C_{\mathrm{FCR-D,downwards}} = \mathbf{min}\left(\frac{\Delta P_{7.5s}}{0.93}, \Delta P_{\mathrm{ss,downwards}}, \frac{E_{7,5s}}{3.7s}\right) \qquad (3.32)$$

### 4.4.3 Evaluation of FCR-D Downwards requirements for dynamic performance for deactivation

TBD

### 4.4.4 Evaluation of FCR-D Downwards requirements for dynamic stability

The dynamic stability requirements are confirming that the response of the FCR-D Downwards provision is contributing correctly to damp frequency oscillations in the system.

Compliance with the FCR-D dynamic stability requirement is evaluated using the Nyquist-criteria for the open loop transfer function, given by equations (3.33) and (3.34). $F(s)$ is the transfer function of the FCR providing entity, as described in Subsection 4.1. Note that the requirement applies also to the interpolated values between the tested period times.

$$|1 - \mathrm{F}(\mathrm{s})\mathrm{G}_{min}(\mathrm{s})| < \left|\frac{1}{M_s}\right| \tag{3.33}$$

$$Re\{1 - \mathrm{F}(\mathrm{s})\mathrm{G}_{\mathrm{min}}(\mathrm{s})\} > -1 \text{ when } Im\{1 - \mathrm{F}(\mathrm{s})\mathrm{G}_{\mathrm{min}}(\mathrm{s})\} = 0 \tag{3.34}$$

Where

$$G_{min}(s) = -\frac{\Delta P_{ss}}{C_{FCR-D,Downwards}} \frac{1450\ \mathrm{MW}}{0.4\ \mathrm{Hz}} \frac{f_0}{S_{\mathrm{n,wc}}} \frac{1}{2H_{\mathrm{min}}s + K_{\mathrm{f,min}} * f_0} = -\frac{\Delta P_{ss}}{C_{FCR-D,Downwards}} \frac{7.88}{10.43\ s + 0.25}\ [\mathrm{p.u.}] \tag{3.35}$$

And,

$M_s$ is 2.31

$s$ is the Laplace operator

$f_0$ is 50 Hz
where
$S_{\mathrm{n,min}}$ is 23 000 MW
$H_{\mathrm{min}}$ is $\frac{120\ 000\ \mathrm{MWs}}{S_{\mathrm{n,min}}}$
$K_{f,\mathrm{min}}$ is 0.005 (the load frequency dependence)

$\mathrm{F}(s)$ is given in per unit.

Compared to stability evaluation for FCR-N, the factor $\frac{\Delta P_{ss,downwards}}{C_{FCR-D,Downwards}}$ is included to account for possible performance scaling, and is applicable in cases where the FCR providing unit is unable to fully comply with the performance criteria, but is allowed to sell the part of the stationary capacity under the precondition that it is accounted for in the stability evaluation.

The Nyquist-diagram can be visualized as in Figure 29. The graphical representation of the stability criteria, is that the Nyquist-curve created by the transfer function values and the interpolation between them, should not enclose the point (-1,0) and should not pass inside the stability margin circle.

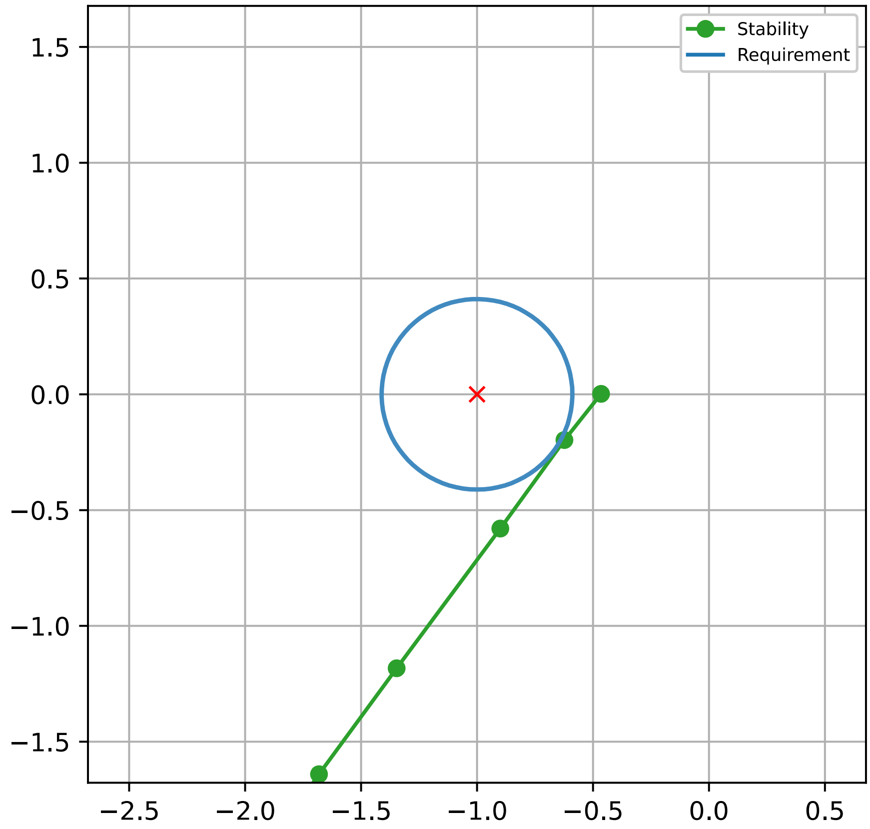



**Figure 29: FCR-N stability requirement (blue) together with an example response (green).**

## 4.5 Evaluation of requirement of switch over between FCR-N and FCR-D

Requirements for entities providing both FCR-N and FCR-D by switching of parameters is verified by documenting the stationary delivery of the entity at 49.5 Hz or 50.5 Hz for FCR-D Upwards and FCR-D Downwards respectively. The total stationary FCR response shall be equal to the sum of the two individual stationary responses of FCR-N and FCR–D with their respective parameter sets.

Referring to Subsection 3.1.1, 3.2.1 and 3.3.1 the relevant values are found the results from the step response sequence results illustrated in Figure 20, Figure 24 and Figure 27. These are summarized in and

The verification criteria for FCR-N and FCR-D Upwards, referring to Table 4, is given as

$$|\Delta P_0| - |\Delta P_2 + \Delta P_3| - |\Delta P_1| < 0.05 \cdot |\Delta P_0| \quad (3.36)$$

The verification criteria for FCR-N and FCR-D Downwards, referring to Table 5, is given as

$$|\Delta P_0| - |\Delta P_2 + \Delta P_3| - |\Delta P_3| < 0.05 \cdot |\Delta P_0| \quad (3.37)$$

**Table 4: Relevant values for showing compliance for switching between FCR-N and -D Upwards**

| Relevant test results | Value | Notation referring to figures |
|---|---|---|
| From Figure 24 (FCR-D upwards) | Combined FCR-N and FCR-D steady state activation | $|\Delta P_0|$ |

| | | |
|---|---|---|
| From Figure 24 (FCR-D upwards) | FCR-D steady state activation | $\lvert\Delta P_2 + \Delta P_3\rvert$ |
| From Figure 20 (FCR-N) | FCR-N stationary capacity | $\lvert\Delta P_1\rvert$ |

**Table 5: Relevant values for showing compliance for switching between FCR-N and -D Downwards**

| Relevant test | Value | Notation referring to figures |
|---|---|---|
| From Figure 27 (FCR-D downwards) | Combined FCR-N and FCR-D steady state activation | $\lvert\Delta P_0\rvert$ |
| From Figure 27 (FCR-D downwards) | FCR-D steady state activation | $\lvert\Delta P_2 + \Delta P_3\rvert$ |
| From Figure 20 (FCR-N) | FCR-N stationary capacity | $\lvert\Delta P_3\rvert$ |

## 4.6 Evaluation of linearity requirement

For FCR providing entities performing the linearity tests of section 3.4.2, the compliance is evaluated by confirming that the measurement results are in line with the linearity requirement, i.e. that the response is within the blue area of the requirement.

The measured FCR response scaled by the capacity shall be plotted against the instantaneous frequency deviation. For FCR-N, this is illustrated in Figure 30 with the linearity requirement indicated by the blue area. The coordinates of the blue area are given in Table 6. Note that the actual test will contain more data-points.

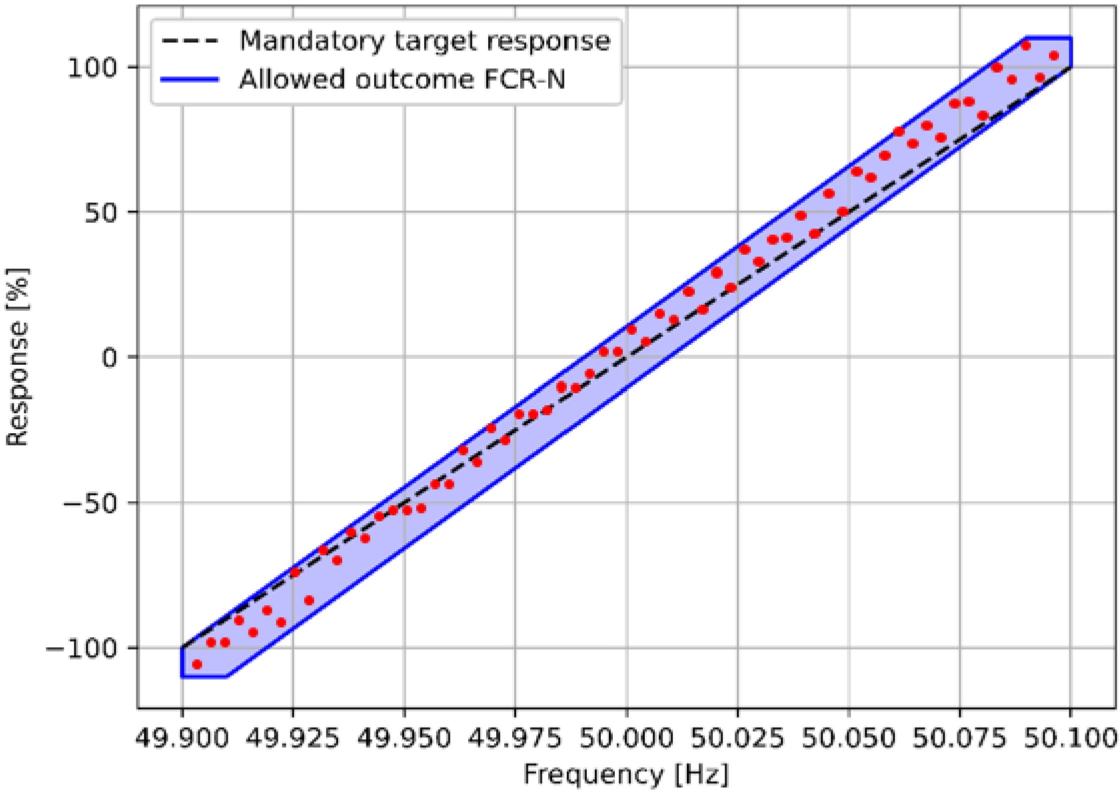



**Figure 30. Example response (red dots) of stationary activation of FCR-N for a demand response FCR providing entity, compared to requirement for linearity (blue area).**

**Table 6. Coordinates of the corners in Figure 30.**
**Counter-clockwise starting from the minimum activation at 49.9 Hz.**

| Frequency [Hz] | Response [%] |
|---|---|
| 49.90 | -100 |
| 49.90 | -110 |
| 49.91 | -110 |
| 50.10 | 100 |
| 50.10 | 110 |
| 50.09 | 110 |
| 49.90 | -100 |

Similarly, the plots for FCR-D is illustrated in Figure 31 with the linearity requirement described by Table 7. Note that the actual test will contain more data-points.

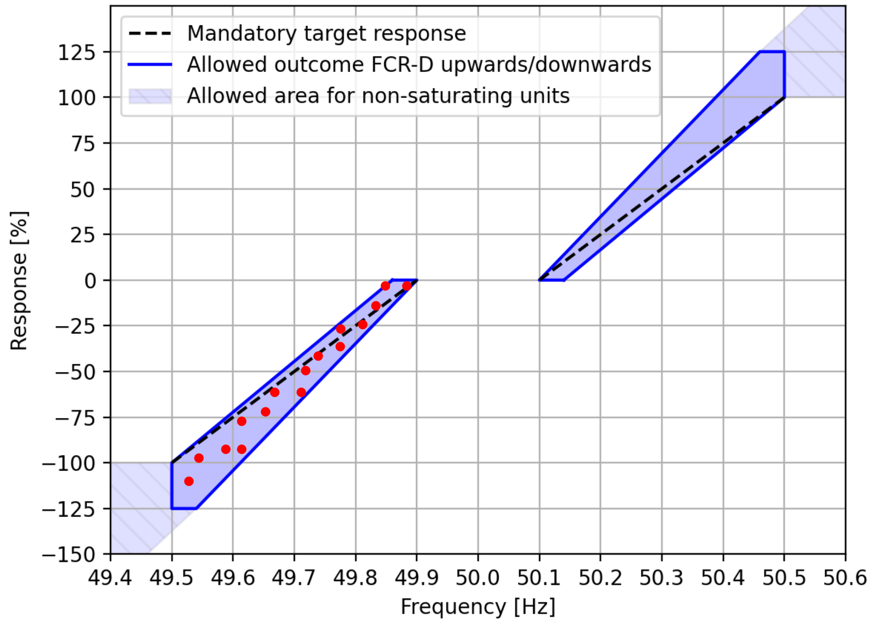



**Figure 31. Example response (red dots) of stationary activation of FCR-D Upwards for a demand response FCR providing entity, compared to requirement for linearity (blue area).**

**Table 7. Coordinates of the corners in Figure 31. Counter-clockwise starting from the minimum activation at 49.9 Hz and 50.1 Hz respectively. Left FCR-D upwards regulation, right FCR-D downwards regulation.**

| Frequency [Hz] | Response [%] |
|---|---|
| 49.90 | 0.0 |
| 49.86 | 0.0 |
| 49.50 | -100 |
| 49.50 | -125 |
| 49.54 | -125 |
| 49.90 | 0.0 |

| Frequency [Hz] | Response [%] |
|---|---|
| 50.10 | 0.0 |
| 50.14 | 0.0 |
| 50.50 | -100 |
| 50.50 | -125 |
| 50.46 | -125 |
| 50.10 | 0.0 |

## 4.7 Capacity determination for operational points within the tested interval

The capacity will in general be determined at four operational points, i.e. the four combinations of

[maximal setpoint, minimal setpoint, highest droop, lowest droop] = $[sp_{max}, sp_{min}, ep_{max}, ep_{min}]$,

as described in Section 3. The capacities are for each operational point are determined by equation (3.13)for FCR-N, equation (3.25)for FCR-D upwards and equation (3.32) for FCR-D downwards.

When the maximal capacity ($C_{max}(sp)$), i.e. capacity for the lowest droop ($ep_{min}$), has been determined for the highest and lowest setpoint in the tests ($sp_{max}, sp_{min}$), the maximal capacity for any setpoint in between ($C_{max}(sp)$) can be calculated through linear interpolation. Correspondingly the minimal capacity ($C_{min}(sp)$) for any setpoint can be calculated from the minimal capacity for the highest and lowest setpoint. Thus, the maximal capacity (from the lowest droop setting) and the minimal capacity (from the highest droop setting) can be calculated for any setpoint in between the highest and lowest setpoint.

The actual capacity ($C$) for the operational point is determined not only by setpoint, but also by the droop setting. The capacity for any droop setting $C(ep)$ is determined by linear interpolation of the capacity from the lowest droop ($C_{max}$) and the capacity from the highest droop ($C_{min}$), which in turn are interpolated for the setpoint per the previous paragraph. The interpolations are described mathematically in Equation(3.38).

$$C_{max}(sp) = C_{max}(sp_{min}) + [C_{max}(sp_{max}) - C_{max}(sp_{min})] \cdot \left[\frac{sp - sp_{min}}{sp_{max} - sp_{min}}\right]$$

$$C_{min}(sp) = C_{min}(sp_{min}) + [C_{min}(sp_{max}) - C_{min}(sp_{min})] \cdot \left[\frac{sp - sp_{min}}{sp_{max} - sp_{min}}\right]$$

$$C(ep) = C_{min} + [C_{max} - C_{min}] \cdot \left[\frac{ep - ep_{min}}{ep_{max} - ep_{min}}\right] \tag{3.38}$$

$$C(sp, ep) = 0, \quad \text{if} \begin{cases} sp > sp_{max} \\ sp < sp_{min} \\ ep > ep_{max} \\ ep < ep_{min} \end{cases}$$

This procedure is valid for both FCR-N and FCR-D. If the entity is tested at more than 2 setpoint values or more than two droop levels, the linear interpolation is done based on the two tested corresponding values in-between which the sought value lies.

The above given set of equations are examples to indicate how the interpolation in general shall be performed. If the equations have to be modified to suit an FCR providing entity this shall be documented in the application and approved by the reserve connecting TSO.

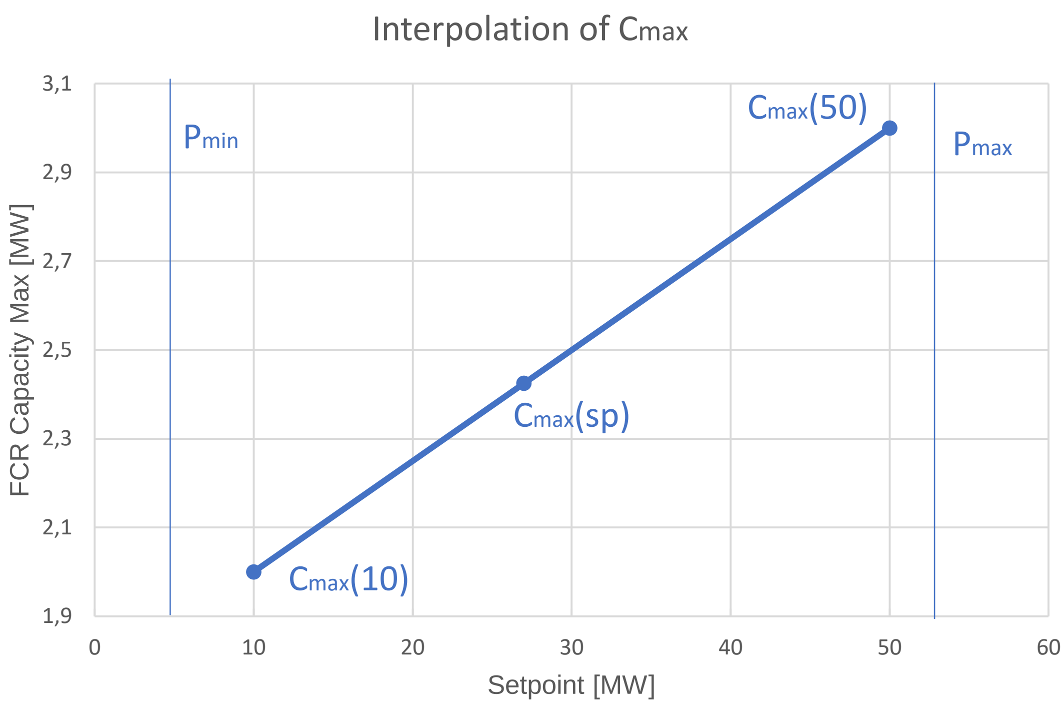



**Figure 32. First step of the linear interpolation to determine the maximal capacity for setpoints between the minimum and maximum tested setpoint.**

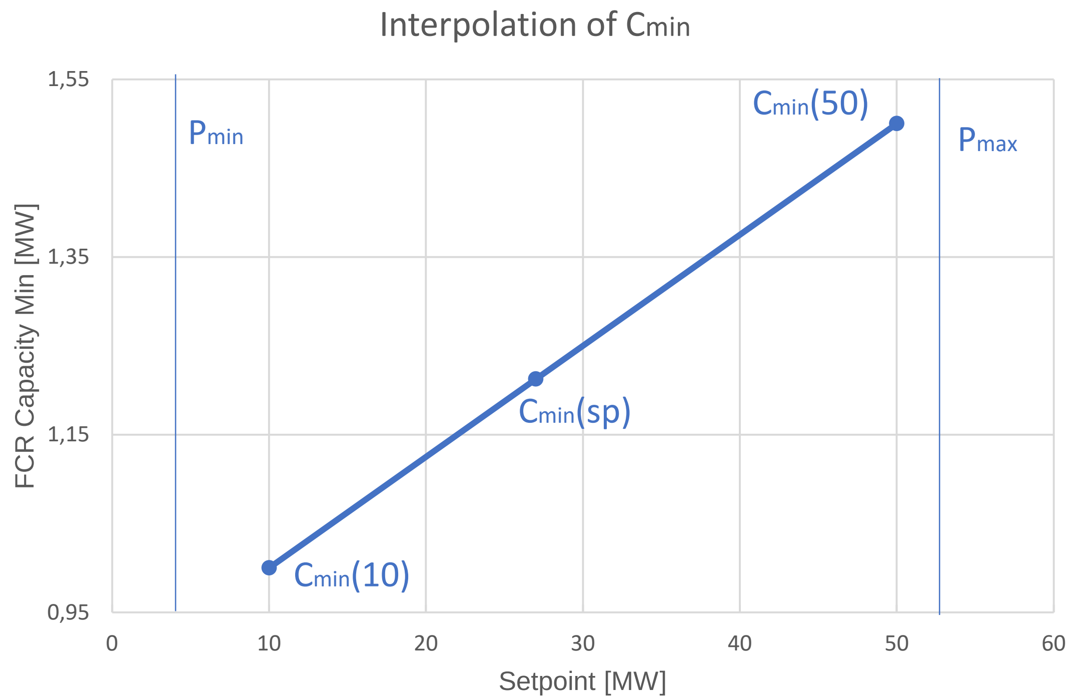



**Figure 33. Second step of the linear interpolation to determine the minimal capacity for setpoints between the minimum and maximum tested setpoint.**

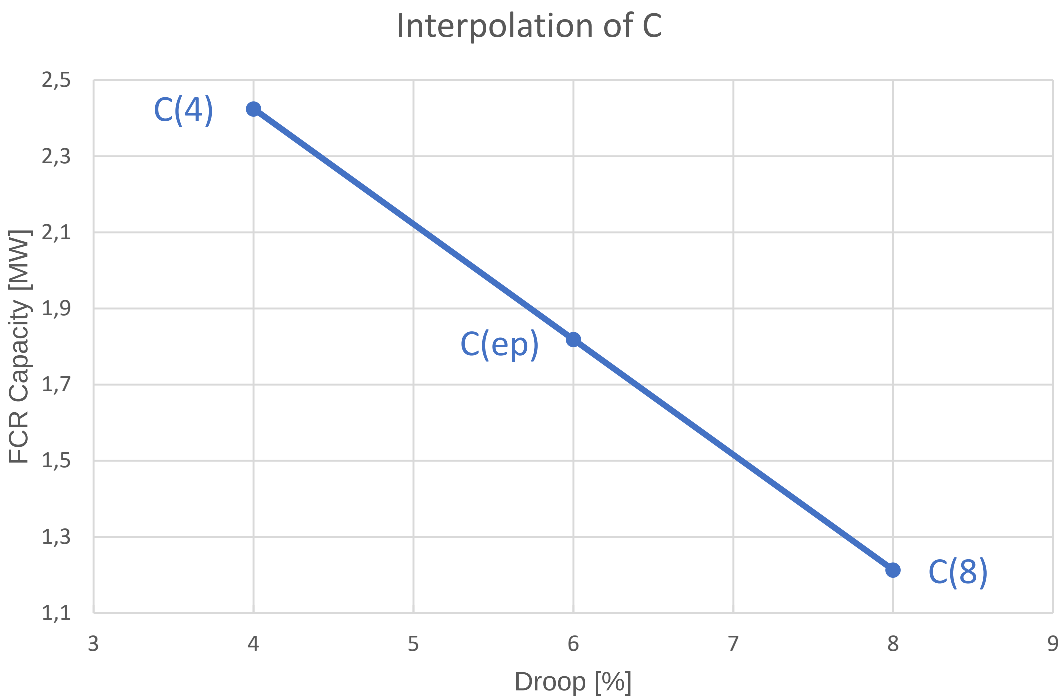



**Figure 34. Third step of the linear interpolation to determine the actual capacity for droop levels between the minimum and maximum tested droop.**

Once the maximum and minimum capacity are determined for the maximum and minimum setpoint, the prequalified capacities in between can be calculated with Equation (3.38) as shown by the examples below. The tests have in the example been performed for two setpoint, 10 MW and 50 MW, and two droop levels, 4% and 8%. The test results are summarised in Table 8 below. The interpolation is also shown graphically in Figure 32, Figure 33 and Figure 34.

**Table 8. Example outcome of testing at four operational points.**

| Setpoint [MW] | Droop [%] | Capacity [MW] |
|---|---|---|
| 10 | 4 | 2 |
| 50 | 4 | 3 |
| 10 | 8 | 1 |
| 50 | 8 | 1,5 |

Assume that the capacity shall be calculated if a setpoint of 27 MW and a droop level of 6% are chosen. By application of Equation (3.38):

$$C_{max}(27) = 2 + (3-2)\frac{27-10}{50-10} = 2{,}425\ MW$$

$$C_{min}(27) = 1 + (1{,}5-1)\frac{27-10}{50-10} = 1{,}2125\ MW$$

$$C(6) = 1{,}2125 + (2{,}425 - 1{,}2125)\frac{6-4}{8-4} = 1{,}82\ MW$$

## 4.8 Capacity determination for uncertain or varying responses

The delivered response from an FCR providing entity may be partly uncertain, due to e.g. stochastic or periodic consumption of the entity. The delivered response shall then be calculated as the difference between the active power output after the activation, and the active power output that would have occurred if the entity had remained not activated. This is illustrated for two types of varying loads in Figure 35 and Figure 36.

Example 1 illustrates a situation where the load variations are independent of if the entity has been activated or not. If it is possible to determine that the variations are independent of activation they will be excluded from the capacity calculation during prequalification and operation. To do this assessment the application has to include suitable data and documentation.

Example 2 illustrates a situation where the variations are not independent of the delivery. In such a case the capacity shall be determined from the maximal response that is ensured, i.e. the minimum of the response curve after activation.

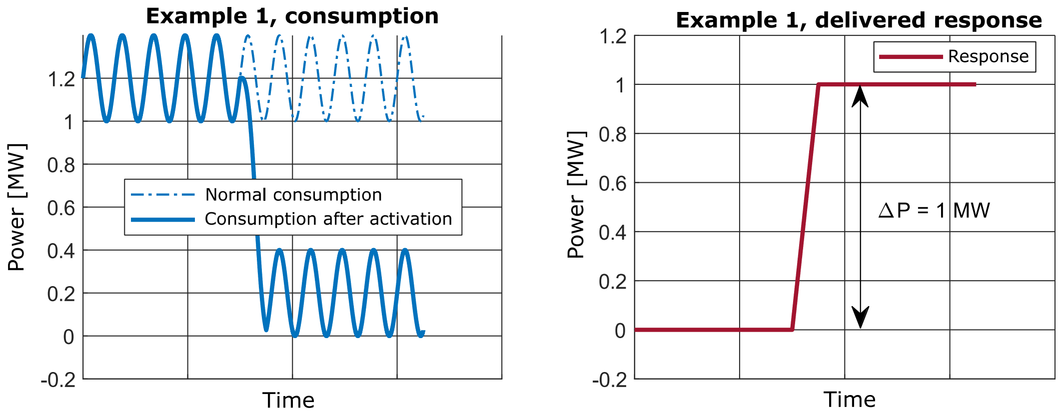



**Figure 35. Example response where variations are independent of the delivered response.**

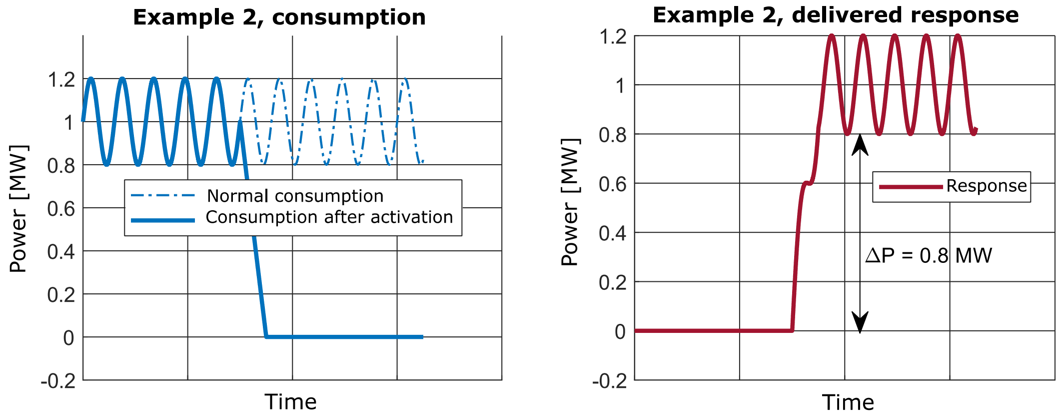



**Figure 36. Example response where the variations are not independent of the delivered response.**

# 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 behaviour 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 4.7, has to be available for activation. 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), $C_{FCR-N,maintained}$, can be calculated according to

$$\mathbf{C_{FCR-N,maintained} = min\left(P_{max} - P_{setpoint}, P_{setpoint} - P_{min}, C_{FCR-N}\left(P_{setpoint}\right)\right)} \quad (5.1)$$

where
$P_{\text{max}}$ is the current maximum power output
$P_{\text{min}}$ is the current minimum power output
$P_{\text{setpoint}}$ is the current power setpoint
$\boldsymbol{C}_{\mathbf{FCR-N}}(sp, ep)$ is calculated as in Equation (3.38)

This calculation is illustrated in Figure 37.

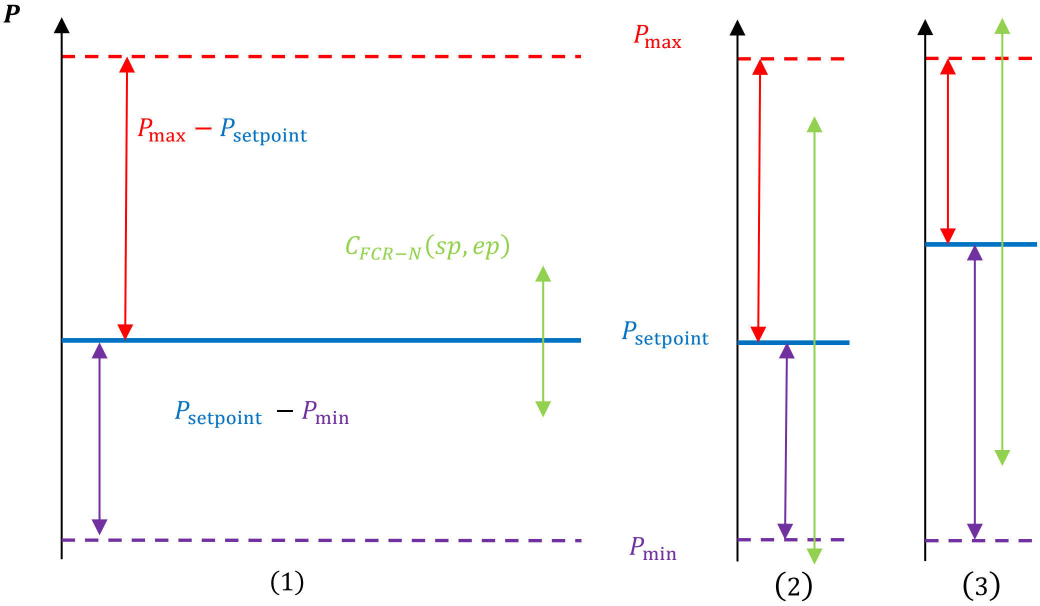



**Figure 37: The three limits of FCR-N capacity for a unit which is limited either by prequalification test result (1), minimum active power (2) or maximum active power (3).**

$C_{\text{FCR-N}}$ 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

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

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

This calculation is illustrated in Figure 38.

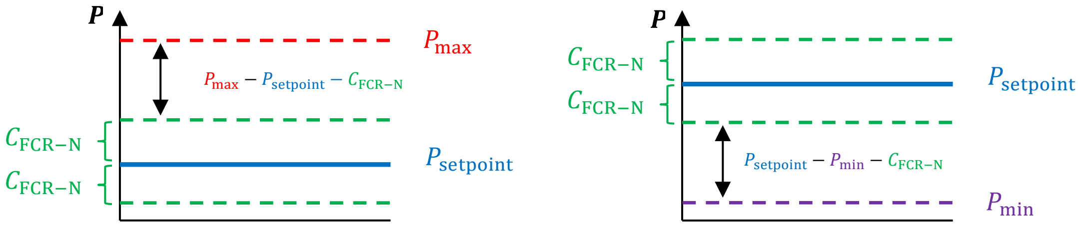



**Figure 38: The limits of FCR-D capacity for a unit which is limited either by maximum active power or minimum active power while delivering FCR-N (FCR- D upwards in the left figure and FCR-D downwards in the right).**

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

## 5.3 FCR providing entities with limited energy reservoir (LER)

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 (5.4) to (5.10)

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).

$$L_{\text{FCR-N}} = \text{limited if} \begin{cases} \mathrm{E}_{\text{reservoir max}} < \mathrm{E}_{\text{current reservoir}} + \\ + \left(\mathrm{P}_{\text{reservoir inflow}} - \mathrm{P}_{\text{setpoint}} + \mathbf{C}_{\text{FCR-N}}(\mathrm{sp},\mathrm{ep})\right) * \mathrm{t}_{\text{req}} \\ \text{or} \\ \mathrm{E}_{\text{reservoir min}} > \mathrm{E}_{\text{current reservoir}} + \\ + \left(\mathrm{P}_{\text{reservoir inflow}} - \mathrm{P}_{\text{setpoint}} - \mathbf{C}_{\text{FCR-N}}(\mathrm{sp},\mathrm{ep})\right) * \mathrm{t}_{\text{req}} \end{cases} \tag{5.4}$$

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

$$\mathbf{L}_{\text{FCR-N endurance,upwards}} = \left| \frac{\boldsymbol{E}_{\text{current reservoir}}}{\boldsymbol{P}_{\text{setpoint}} - \boldsymbol{P}_{\text{reservoir inflow}} + \boldsymbol{C}_{\text{FCR-N}}(\boldsymbol{sp},\boldsymbol{ep})} \right| * \mathbf{60}\ [\boldsymbol{minutes}] \tag{5.5}$$

$$\mathbf{L}_{\text{FCR-N endurance,downwards}} = \left| \frac{\boldsymbol{E}_{\text{current reservoir}}}{\boldsymbol{P}_{\text{setpoint}} - \boldsymbol{P}_{\text{reservoir inflow}} + \boldsymbol{C}_{\text{FCR-N}}(\boldsymbol{sp},\boldsymbol{ep})} \right| * \mathbf{60}\ [\boldsymbol{minutes}] \tag{5.6}$$

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

$$L_{\text{FCR-D downwards}} = \text{limited if} \begin{cases} E_{\text{reservoir max}} < E_{\text{current reservoir}} + \\ \left(P_{\text{reservoir inflow}} - P_{\text{setpoint}} + C_{FCR-D\ downwards}(sp,ep)\right) * t_{\text{req}} \end{cases} \tag{5.7}$$

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

$$\mathbf{L}_{\text{FCR-N endurance,downwards}} = \left| \frac{\boldsymbol{E}_{\text{reservoir max}} - \boldsymbol{E}_{\text{current reservoir}}}{\boldsymbol{P}_{\text{reservoir inflow}} - \boldsymbol{P}_{\text{setpoint}} + \boldsymbol{C}_{\text{FCR-D downwards}}(\boldsymbol{sp},\boldsymbol{ep})} \right| \mathbf{60}\ [\boldsymbol{minutes}] \tag{5.8}$$

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

$$\boldsymbol{L}_{\text{FCR-D upwards}} = \text{limited if} \begin{cases} \boldsymbol{E}_{\text{reservoir max}} > \boldsymbol{E}_{\text{current reservoir}} + \\ \left(\boldsymbol{P}_{\text{reservoir inflow}} - \boldsymbol{P}_{\text{setpoint}} - \boldsymbol{C}_{FCR-D\ upwards}(\boldsymbol{sp},\boldsymbol{ep})\right) * \boldsymbol{t}_{\text{req}} \end{cases} \tag{5.9}$$

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

$$L_{\text{FCR-D up endurance}} = \left| \frac{E_{\text{current reservoir}} - E_{\text{reservoir min}}}{P_{\text{setpoint}} + C_{\text{FCR-D upwards}}(sp,ep) - P_{\text{reservoir inflow}}} \right| 60 \text{ [minutes]} \tag{5.10}$$

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 modifications to the procedure where applicable.

## 5.4 Activated FCR capacity calculation

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

$$\boldsymbol{A}_{\mathbf{FCR}} = \boldsymbol{P}_{\mathbf{actual}} - \boldsymbol{P}_{\mathbf{setpoint}} - \boldsymbol{P}_{\mathbf{other\ reserves}} \tag{5.11}$$

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

# 6 Appendices

## Appendix 1: Different graphical representations of FCR dynamic requirements

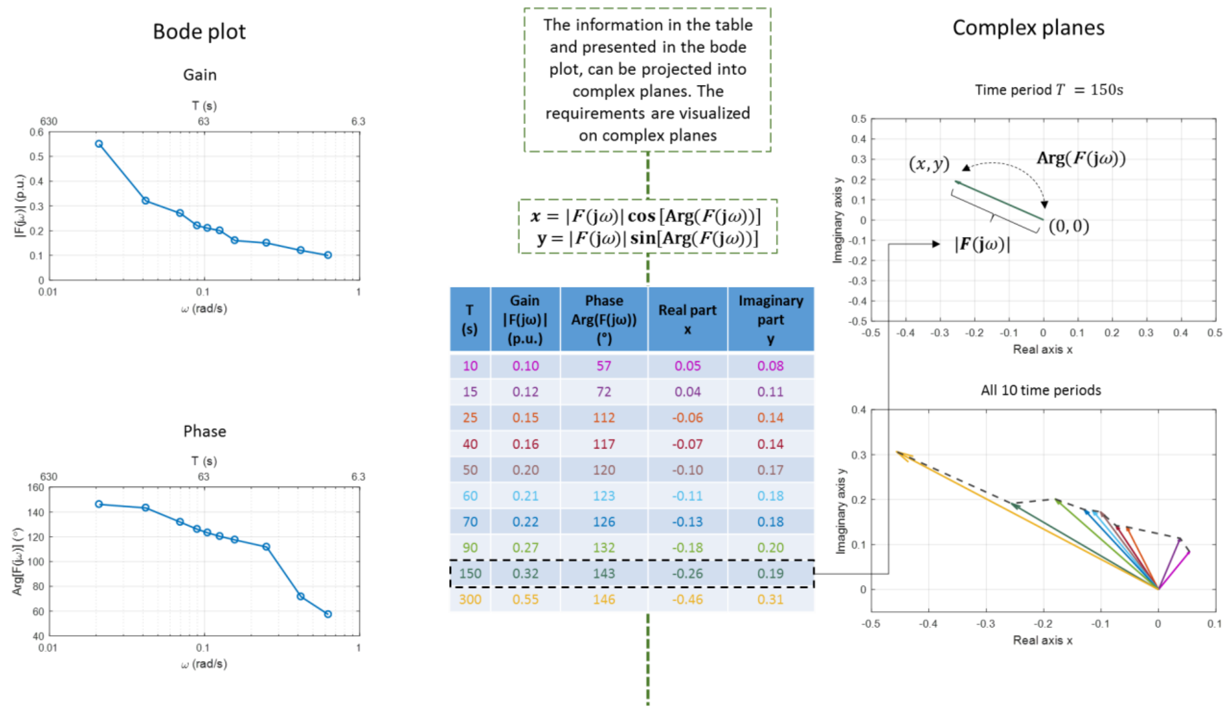
A method for illustrating the FCR providing entity response, is FCR vectors. This uses the same calculations as shown in Subsection 4.1, but presented differently.

Figure 39 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

$$x = |\boldsymbol{F}(\mathrm{j}\omega)|\,\mathbf{cos}\,[\mathbf{Arg}(\boldsymbol{F}(\mathrm{j}\omega))] \qquad \text{(A.1)}$$

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

$$x = |\boldsymbol{F}(\mathrm{j}\omega)|\,\mathbf{sin}\,[\mathbf{Arg}(\boldsymbol{F}(\mathrm{j}\omega))] \qquad \text{(A.2)}$$




| 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 39: Bode plots, transfer function values, FCR-vectors and complex planes**

The requirement circles (dynamic performance and stability) can be plotted in the same 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 9. The circles are visually represented in Figure 40 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 9: Centre coordinates and radiuses for dynamic performance requirement circles**

| Time period (s) | Circle centre (x, y)[5] | 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 |

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

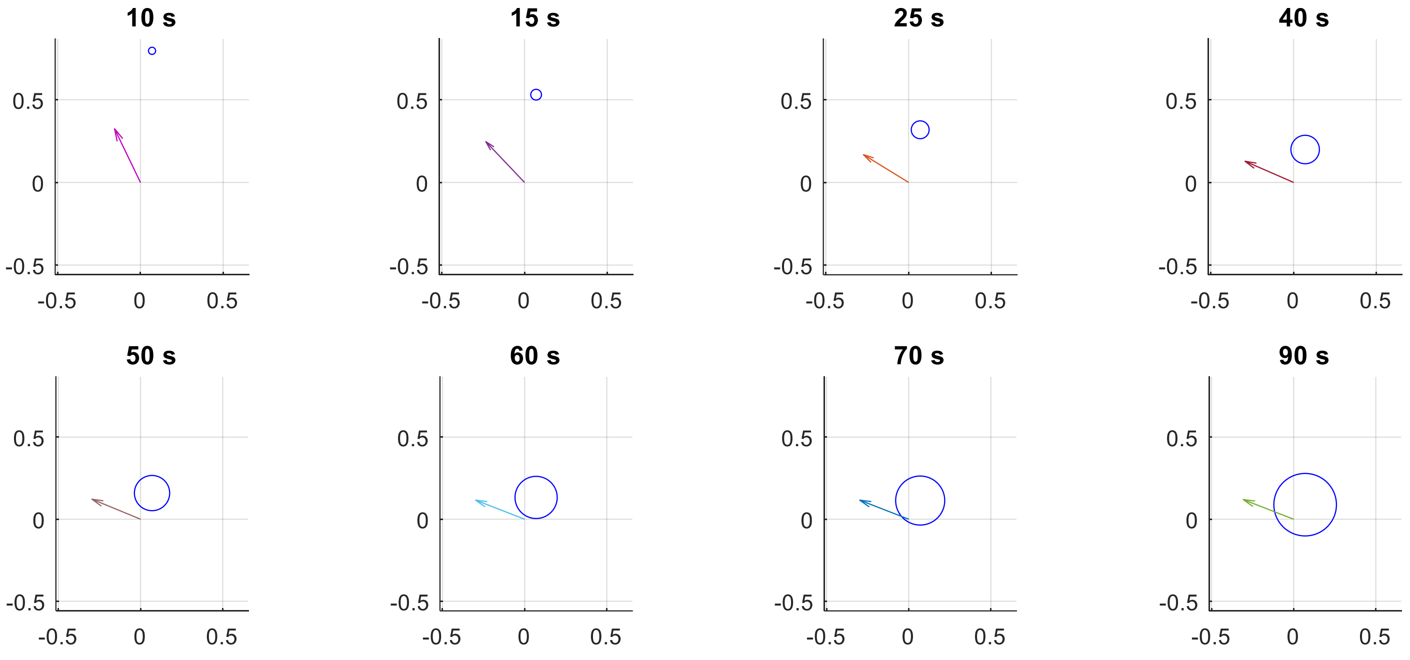



**Figure 40: FCR-N dynamic performance requirement circles and FCR-vectors of an example unit**

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 10. The circles are visually represented in Figure 41 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 10: Centre-coordinates and radiuses of stability requirement circles**

| Time period [s] | Circle centre (x, y)[6] [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 |

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

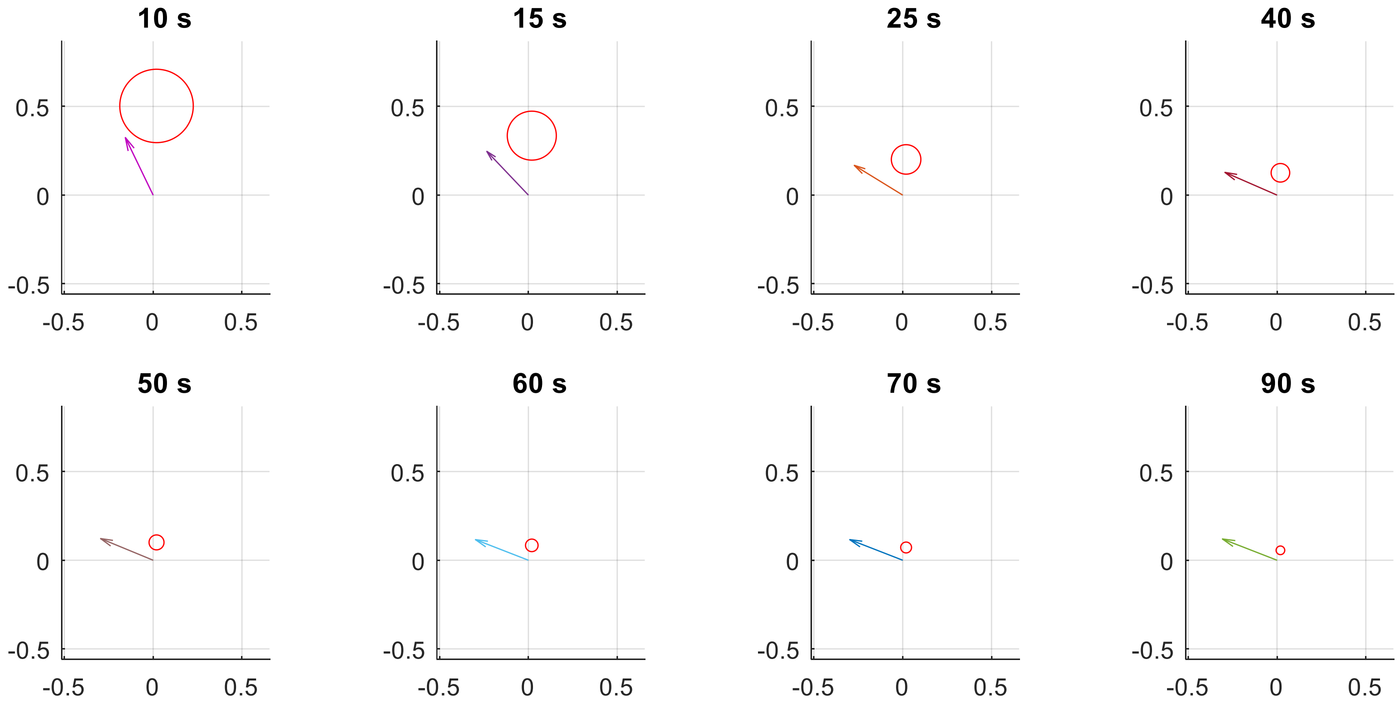



**Figure 41: FCR-N stability requirement circles and FCR-vectors of an example unit**

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