European Network of Transmission System Operators for Electricity

entsoe

FFR Design of Requirements – External document

Version 1.0

Inertia2020 Working Group

AUTHORS

Niklas Modig	Svenska kraftnät
Robert Eriksson	Svenska kraftnät
Mikko Kuivaniemi	Fingrid
Liisa Haarla	Fingrid
Pia Ruokolainen	Fingrid
Knut Hornnes	Statnett
Per Arne Vada	Statnett
Espen Aronsveen	Statnett
Soroush A. Meybodi	Energinet
Daniel Karlsson	DNV GL

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List of Abbreviations

ENTSO-E	European Network of Transmission System Operators for Electricity
EPC	Emergency Power Control (EPC) functionality
EPC_{over}	Emergency Power Control (EPC) functionality at high frequency to increase HVDC export / decrease HVDC import
EPC_{under}	Emergency Power Control (EPC) functionality at low frequency to increase HVDC import / decrease HVDC export
FCR-D	Frequency Containment Reserve for Disturbances
FFR	Fast Frequency Reserve
FFR_{over}	FFR functionality at high frequency to increase load / reduce generation
FFR_{under}	FFR functionality at low frequency to increase generation / reduce load
GWs	Gigawatt seconds
HVDC	High Voltage Direct Current
MW	Megawatt
SO GL	System Operation Guideline
TSO	Transmission System Operator

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1. Background

With the increased focus on power system kinetic energy (also referred to as inertia), the Nordic TSOs have over the years launched several studies, with the aim to improve the knowledge in the topic of frequency stability and system inertia variation. The transient frequency stability in a power system is depending on the reference incident defined as the maximum positive or negative deviation occurring instantaneously between generation and demand in a synchronous area, in this case maximum loss of generation, the system reserves and the inertia level. In [1], [2], and [3] it is shown that the current, draft specification for Frequency Containment Reserve for Disturbances (FCR-D) will not be enough to handle the reference incident in a future low inertia power system.

In the project 'FCR-Design' [3], finalized during 2018, a new FCR-D technical requirement methodology was proposed. The main driver for that project was the issue with low market liquidity, if the FCR-D upwards would be designed to alone ensure transient frequency stability for a reference incident for a low inertia system as designed in [1]. This would result in quite demanding requirements and thereby low capacity offered to the market. The new methodology makes it possible to design the requirements for a higher level of power system inertia. If this is done, it is necessary to implement another solution to ensure transient frequency stability when the actual power system inertia is lower than this design level. It was decided that the other solution should be a fast acting support called Fast Frequency Reserve (FFR) with a shorter time duration, complementing FCR-D upwards [3].

In another of the latest studies, the 'Future System Inertia2 project' [2], long term mitigating measures for handling low system inertia levels to maintain frequency stability margins in the Nordic system was analysed. The "Future System Inertia2 project' also points out the usage of FFR, acting as a complement to FCR-D upwards, as a suitable measure to fulfil the requirements for a reference incident as specified in ENTSO-E SO GL [4].

This document explains the design of the technical requirements for the FFR. Due to time restrictions, tests to verify compliance and capacity verification are not analysed in detail and are not explained in this document.

2. Design considerations

2.1 Overview

The main objective for FCR-D upwards is to secure frequency stability, i.e. that the power system frequency does not decrease below 49.0 Hz. The largest reference incident in the Nordic power system is a trip of the nuclear power plant Oskarshamn 3 at 1450 MW.

An important factor for the frequency stability is the power system kinetic energy. With a lot of synchronous machines connected to the system, there is a lot of rotating mass to absorb or inject power to counteract the frequency change. With lower kinetic energy, seen in the future power system with more inverter based generation, the frequency will change faster, and the FCR-D upwards might not be fast enough to keep the frequency within the normal range.

To ensure transient frequency stability the Nordic TSOs decided to design the FFR to complement the FCR-D upwards when the kinetic energy is low. At the time of the FFR design the updated requirements for the FCR-D upwards are not decided. This makes the design of FFR more challenging since the FFR will complement the FCR-D upwards when the kinetic energy is so low that the FCR-D upwards cannot secure transient frequency stability on its own. The FFR design needs to work in a good way with different FCR-D upwards requirements.

2.2 FCR-D technical requirements

The technical requirements for the FCR-D upwards will not be specified in this design but it has a big impact on the design of the FFR. The requirements for the FCR-D upwards will secure transient frequency

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stability for a reference incident down to a specific level of kinetic energy. This level will be decided in the coming projects based on socio economic analysis. It is important to take into consideration in the FFR design, that the FFR should be applicable to different FCR-D upwards requirements. When the kinetic energy in the power system is lower than the performance design limit for the FCR-D upwards, FFR needs to be procured to secure transient frequency stability.

2.3 FFR support duration

Figure 1 shows the intention of the FFR. It is already decided that FFR will be limited in time to be a compliment to FCR-D upwards, with a faster response [2,3]. When the inertia in the power system is low, the frequency would decrease faster, but then the FFR is activated fast, having a short duration and starts to decrease to shift the burden over to FCR-D.

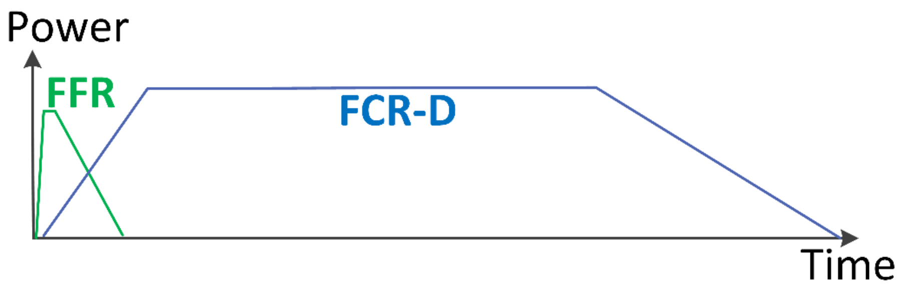

Figure 1: FFR shall be fast with a limited duration, shifting the burden over to FCR-D upwards. The figure illustrates the timely sequence of FFR and FCR-D.

2.4 Full activation time of FFR

The technical requirements should be simple. FFR should be fast acting, in the range of one second, to support FCR-D upwards. Therefore, the full activation time is used as an indication for the performance. The shape of the FFR contribution, from the activation instant to the full activation level (reached at the full activation time), has to be monotonously increasing. Figure 2 shows the type of requirement that shall be designed. The requirement on the full activation time should comply with the power system needs, and with the providers' ability to supply FFR.

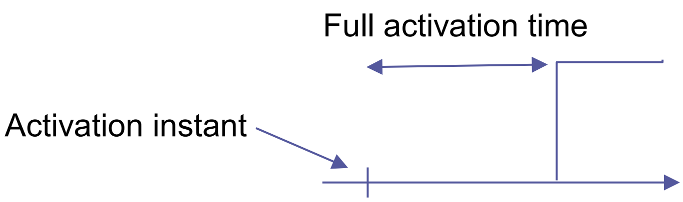

Figure 2: Full activation time should be a performance indicator.

The need for FFR contribution prior to the full activation time is regarded as limited. The activation response will only be designed from the full activation time, i.e. a single step-change is allowed at the full activation time, as any contribution earlier than that would improve the response from a system point of view.

2.5 Frequency triggering level of FFR

The frequency triggering level of the FFR must be chosen to satisfy the system needs. For a lower frequency trigger level, the reserve needs to be faster to secure the transient frequency stability. With a higher triggering level, the reserve will be activated more frequently.

3. Dynamic simulation model

To design the FFR technical requirements, simulations were performed in a lumped single machine model of the power system. The dynamic model used for the simulations is described in [5]. The model is focused to capture the Nordic power system frequency behaviour during transient events in the frequency range 49.9 – 49.0 Hz. The dynamics for the FCR-D upwards is based on the response from a hydro power machine.

FFR is modelled simply as a stepwise active power response with a delay after the frequency has gone under the activation threshold. Deactivation of the FFR is done either step wise or as a ramp.

To mitigate the fact that the simulation model is not fully representing all dynamics of the power system, a safety margin should be added in the requirements.

The FFR activation requirements have been simulated on a wide variety of FCR-D upwards settings to ensure that the FFR will have a good performance with a minimum of dependence on the technical requirements for the FCR-D upwards, since they are not decided.

The deactivation and recovery were, due to time restrictions, only simulated using the FCR-D parameters specified in Table 1. These parameters were estimated during the 'Future System Inertia2 project' [2], and were the best estimates available at the time for the development of the technical requirements.

Table 1: Parameter settings used for deactivation and recovery simulations

Parameters	**Value**
Proportional gain K_p	4
Integral gain K_i	2
Derivative gain K_d	1
Droop [%]	2
Water time constant T_w [s]	0.8
Unit loading [%]	80
FCR-D upwards capacity [MW]	1450
System load [GW]	23
Frequency dependent load [%/Hz]	1

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4. Technical requirements for FFR

The FFR volume is quantified in MW. FFR for underfrequency is defined as a positive value, either as an increase of power infeed to the system or as a load reduction. The requirements studied through simulations in this report are activation, deactivation, recovery and overdelivery. These requirements are considered as the most important FFR requirements to secure the transient frequency stability for the system.

4.1. Activation

FFR is intended to be a fast, active power support, responding to a frequency deviation. To set the frequency activation level and the maximum full activation time, a large number of simulations were performed.

The efficiency of the different FFR activation options was compared to both reducing the reference incident and procuring additional FCR-D upwards. A higher efficiency of the FFR will result in a higher instantaneous frequency minimum. There is a trade-off between efficiency, frequency trigger level and full activation time. Figure 3 shows the instantaneous frequency minimum for five different FFR activation options compared to reduction of the reference incident and additional FCR-D upwards for a loss of 1450 MW and a kinetic energy of 100 GWs[1] for a specific set of FCR-D upwards parameters. The curves labeled c), i.e. FFR activation levels 49.7 Hz (1.3 s), 49.6 Hz (1.0 s), and 49.5 Hz (0.7 s), are all equally efficient with respect to the instantaneous frequency minimum after the reference incident. The 100 GWs kinetic energy is considered a very low inertia situation, and it is used in simulations as a reference case [6]. The simulations are performed with 1450 MW FCR-D upwards capacity. From a performance point of view the FCR-D upward in the simulations is designed to be as typical as possible for normal operational conditions, while the effect of an additional volume has been investigated. The level of kinetic energy in the system affects the FFR volume needed, but the technical requirements stay the same.

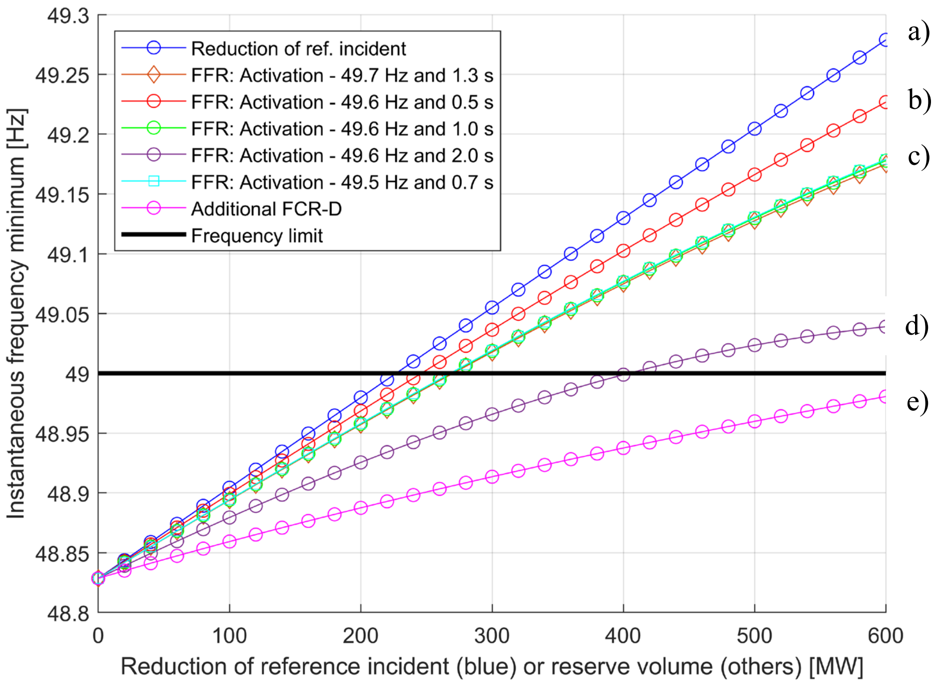

Figure 3: Simulation results of different FFR activation options, for an inertia level of 100 GWs, compared to 1) the reduction of reference incident (1450 MW) and 2) additional FCR-D volume of typical performance and stability settings.

[1] A kinetic energy of 100 GWs is assumed to be the lowest value in the Nordic system for the near future, and is used as a reference value [6].

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By comparing the different FFR activation options, one can see how the efficiency changes when the full activation time increases for the frequency activation level of 49.6 Hz, from 0.5 s (curve b), to 1.0 s (curve c) and 2.0 s (curve d). To ensure an instantaneous frequency minimum above 49.0 Hz, approximately 220 MW with an activation time of 0.5 s, 250 MW with an activation time of 1 s or 400 MW with an activation time of 2 s is needed. Based on this, the 1 second alternative is more efficient compared to the 2 s alternative, with a significantly lower FFR volume requirement (250 MW compared to 400 MW). On the other hand, going down to 0.5 s, only reduced the volume with 30 MW. Therefore, an activation frequency of 49.6 Hz and full activation time of 1s were chosen. To increase the number of alternatives, settings with equal efficiency were found, indicated by the brown, green and light blue lines being almost on top of each other (curve c). The efficiency for these settings is similar for the different FCR-D upwards requirements. Curve (e) in Figure 3, relates to increased FCR-D upwards volume, while curve (a), reduction of the reference incident, is included as a reference.

The FFR activation requirements are presented in Table 2.

Table 2: Fast Frequency Reserve activation requirements

Alternative	Activation level [Hz]	Maximum full activation time [s]
A	49.7	1.30
B	49.6	1.00
C	49.5	0.70

The provider may choose any of the three alternatives A, B, or C.

Figure 4 shows the instantaneous frequency minimum for the three activation alternatives as a function of the of system kinetic energy, with the FFR volume as a parameter; 0, 100, 200 and 300 MW. When the lines are different there is a difference in efficiency between the different alternatives. The figure shows that the efficiency for the three alternatives is very similar.

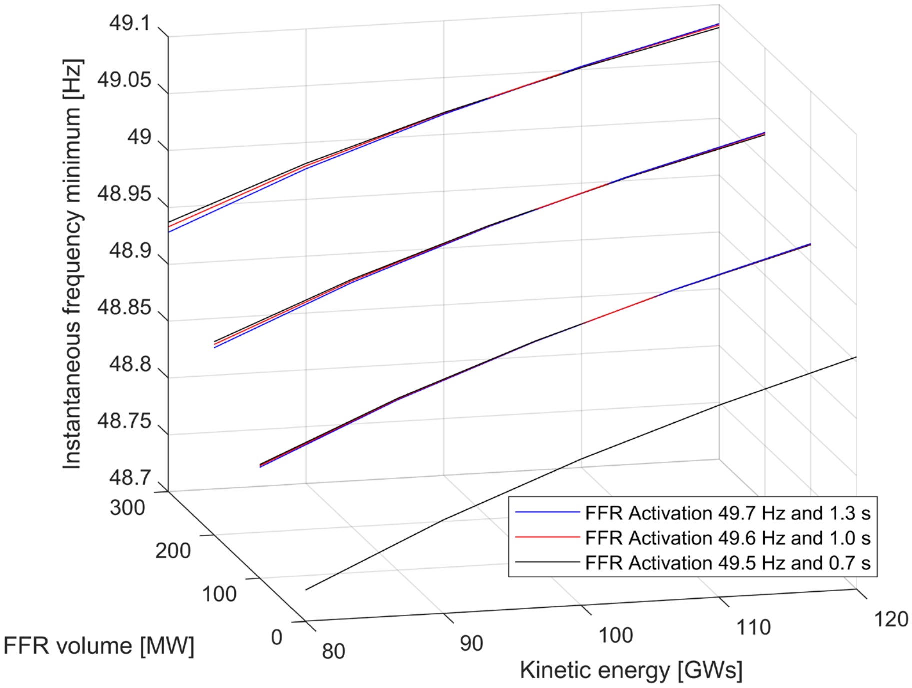

Figure 4: Instantaneous frequency minimum for the three FFR activation alternatives for different kinetic energy and FFR volume.

4.2. Deactivation

To secure a smooth transition of power from the FFR to the FCR-D, the deactivation must be specified. Figure 5 shows a generalisation of the FFR delivery divided into different time periods.

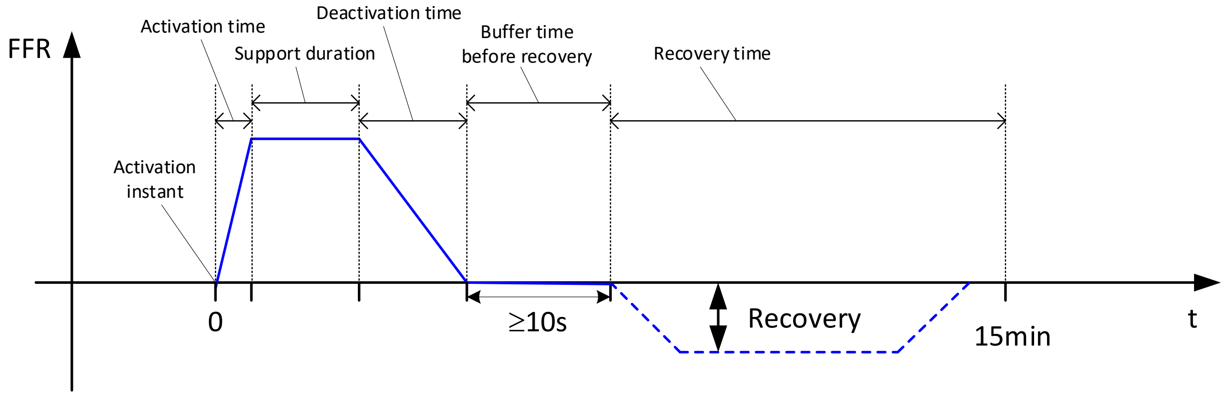

Figure 5: FFR requirement; activation at t = 0.

Two different types of deactivation have been designed in order to fit different FFR sources. In the event of a disturbance it is important that the activated power is not deactivated too fast and too close in time to the actual disturbance. In that case the FCR-D upwards will not be fast enough to take over the burden. The long support duration FFR has been designed such that neither the deactivation time nor the shape of the deactivation is critical, while for the short support duration FFR some restrictions apply. The buffer time before the recovery is set with respect to the present requirements on FCR-D upwards, i.e. 100% after 30 seconds, to ensure that the full FCR-D upwards capacity has been activated.

4.2.1. Long support duration FFR

This is designed for resources without the possibility to control the deactivation in a ramp wise manner. If the deactivation is step wise it is important that the frequency has stabilised before the deactivation occurs. A minimum support duration of 30 seconds is decided and considered as long. There is no limitation in the rate of deactivation for the long support duration FFR; the deactivation can be stepwise. A single step deactivation will create a second frequency dip. By waiting 30 seconds before deactivation there is time for the frequency to stabilize before the deactivation occurs. Figure 6 shows the system response without any FFR for a 1450 MW disturbance in a system of 100 GWs kinetic energy. The FCR-D model parameters are estimated in [2] based on actual system disturbances. The regulating strength during these disturbances is assumed to be higher than the procured volume, hence the steady state frequency is higher than 49.5 Hz.

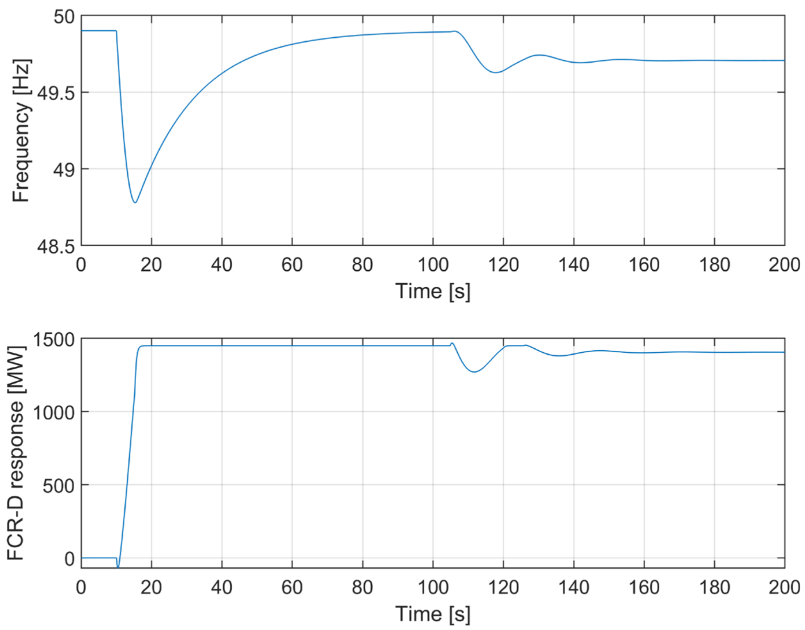

Figure 6: Simulation of system response without FFR.

Figure 7 shows the corresponding results for a system with 500 MW FFR deactivated step wise after 30 seconds.

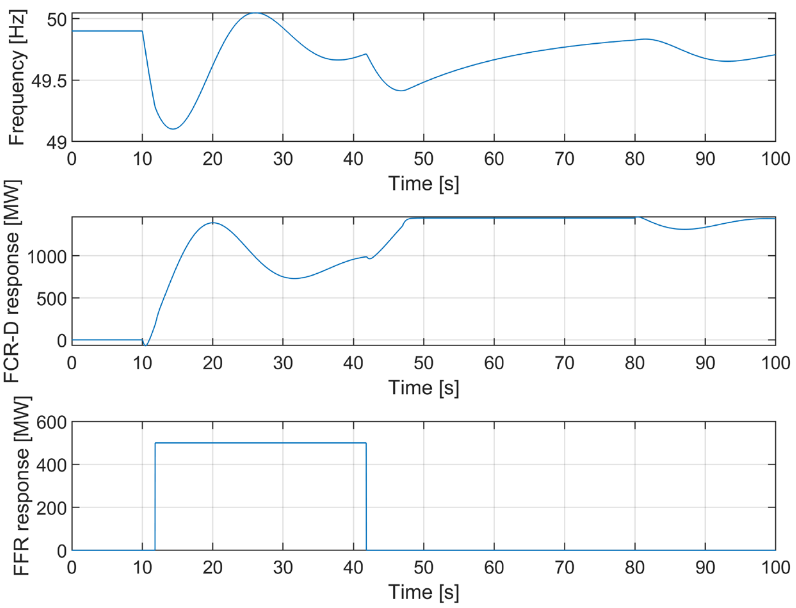

Figure 7: 500 MW FFR using a long support duration of 30 s and a single step deactivation.

The reason why the steady state frequency is higher compared to 49.5 Hz is that the estimated droop during the estimation process was low; 2%. This results in a high share of activated capacity for a small frequency disturbance. To fully map to the activation levels of 49.9 – 49.5 Hz the droop must be selected based on the capacity, frequency dependent load and kinetic energy. Between 47 s and 80 s the gate limiter is limiting the output to 1 p.u. After 80 s the governor output is reducing below the limit, leading to a reduction of power. The steady state frequency in this case is 49.71 Hz. At 80 s when the FCR-D contribution starts its reduction, the frequency is 49.83 Hz.

4.2.2. Short support duration FFR

For units with the ability to reduce the response in a smooth way there is no need to wait for the long duration of 30 s. The smooth deactivation will put less stress on the FCR-D and thereby the duration doesn't need to be that long. Figure 8 shows simulation results for 500 MW FFR with a 2 second duration and 20 %/s deactivation speed.

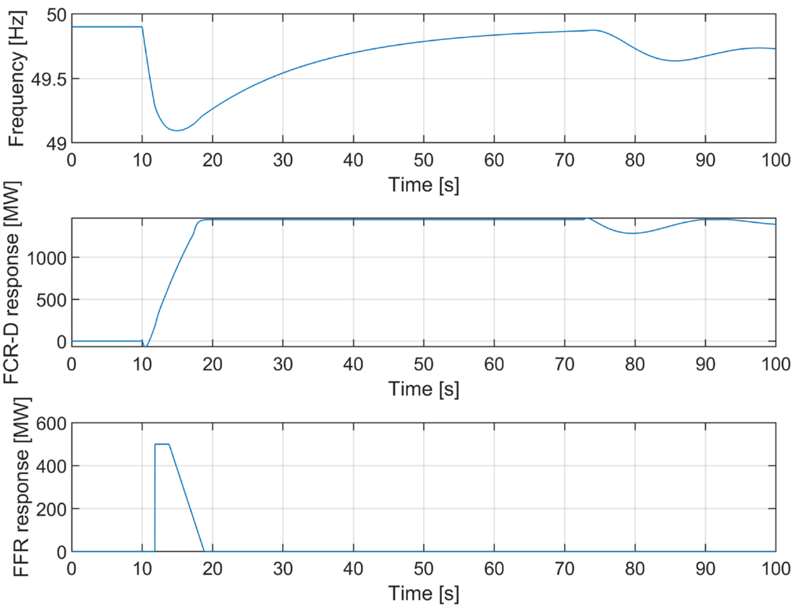

Figure 8: 500 MW FFR using a short support duration of 2 s and a deactivation of 20 %/s.

The simulations showed that 2 seconds were enough for 500 MW FFR in a low inertia power system. The minimum support duration for the short support duration FFR was decided to 5 s in order to have some extra margin. The rate of deactivation is limited to maximum 20% of the actual FFR provision per second. If a higher ramp rate is used there is a risk that the FCR-D won't respond in time and that the frequency starts to decrease. Between 47 s and 80 s the gate limiter is limiting the output to 1 p.u. After 80 s the governor output is reduced below the limit, leading to an output power reduction. The steady state frequency in this case is 49.71 Hz. At 80 s when the FCR-D starts to reduce, the frequency is 49.83 Hz. Also, in this simulation the steady state frequency is higher than 49.5 Hz, since the estimated droop was low; 2%.

4.3. Overdelivery

Some potential FFR providers have declared problems with limiting the FFR provision to the value reached one second after the activation instant (or 0.7 s and 1.3 s if the FFR is activated at those corresponding frequency levels). The risk with overdelivery of FFR is that it leads to overfrequency that in turn triggers other services such as overfrequency triggered EPC and also a possible future overfrequency activated FFR. Overdelivery is defined as the maximum instantaneous amount of power exceeding the FFR capacity of the unit, as shown in Figure 9.

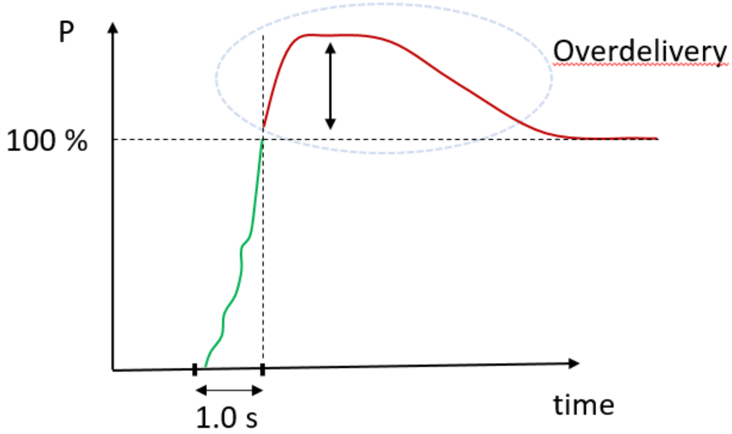

Figure 9: Definition of overdelivery relative to the FFR capacity.

For overdelivery, a smaller disturbance is more severe as the imbalance might become overcompensated. Worst case occurs if all FFR is activated as a step at the same frequency. In this study 49.6 Hz was chosen as the frequency activation level. Figure 10 shows the results of a simulation of a smaller disturbance of 450 MW in a system with 100 GWs kinetic energy. The amount of FFR comes from the calculations made to ensure an instantaneous frequency minimum above 49.0 Hz using 1450 MW as the reference incident leading to procurement and activation of 500 MW of FFR. Six different levels of overdelivery are represented in Figure 10.

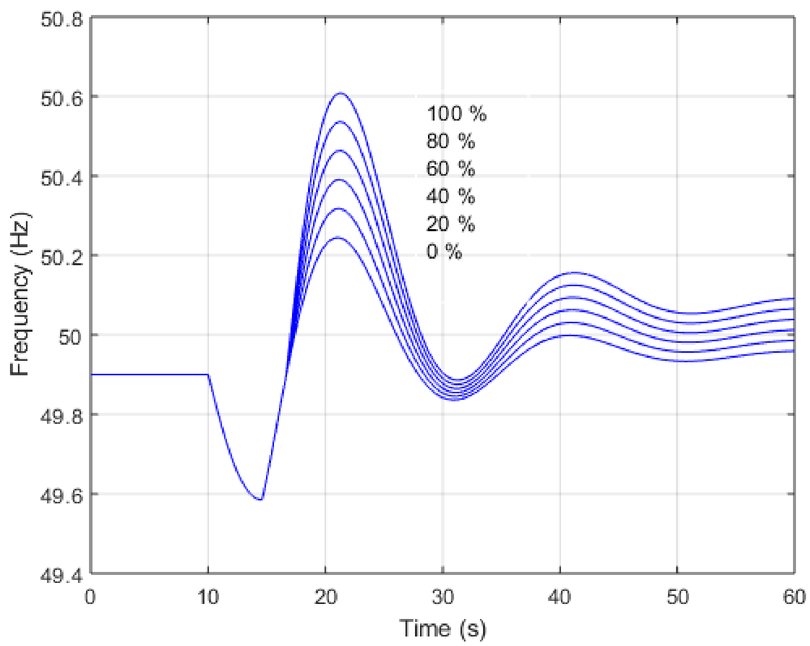

Figure 10: 500 MW FFR and 150 MW EPC activated for a disturbance of 450 MW.

The first EPC_{over} activation for overfrequency starts at 50.3 Hz and FFR for overfrequency will have the same activation level if mirrored to the current requirements. To avoid reaching this frequency, system level overshoot should not exceed 20%. The per entity requirement is set to 35% awaiting further studies. The national maximum overdelivery target is limited to 20% to ensure the system requirement of maximum 20%.

4.4. Recovery Requirements

The FFR providing entities must be fully prepared for a new activation cycle within 15 minutes from the initial activation. Some entities might need to recover the energy delivered in order to deliver again. The recovery is illustrated in the generalisation of FFR in Figure 5.

The recovery shall not start until after the frequency nadir is passed and a stable frequency recovery governed by the FCR-D is in place. Appropriate time requirements were examined and determined through simulations. The conclusion was that the recovery must not start before a time corresponding to the activation time + support duration + deactivation time + 10 seconds, has elapsed from the activation instant as illustrated in Figure 5. The margin of 10 seconds is to ensure that FCR-D has the time to stabilise the frequency prior to recovery. The recovery, according to Figure 5, must not exceed 25% of the actual FFR provision. Figure 11 shows simulation results of 500 MW FFR (short duration i.e. 5 seconds) with a recovery of 25% starting 10 seconds after the deactivation.

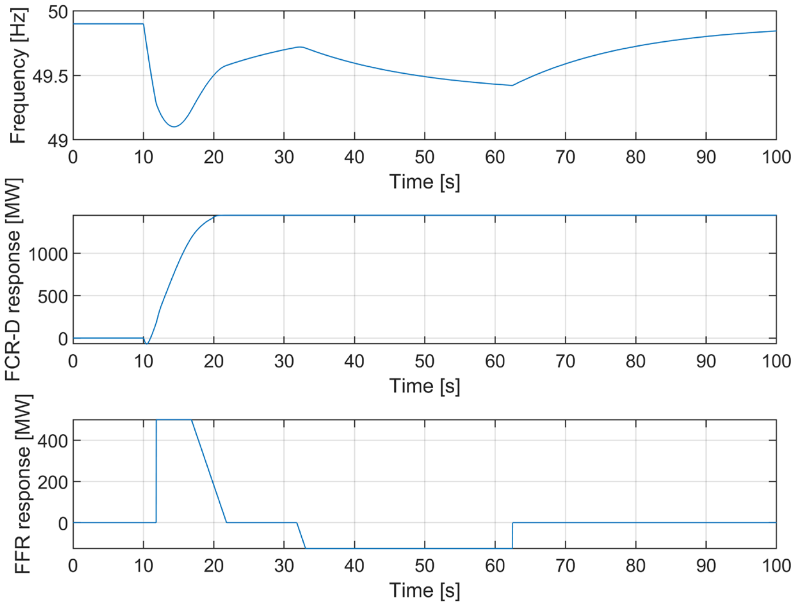

Figure 11: 500 MW FFR using a short duration of 5 s and a deactivation of 20 %/s. Recovery of 25 % of the FFR capacity (“negative FFR response”) starts 10 seconds after deactivation.

The major change introduced by allowing recovery is that the frequency starts to fall when the recovery starts. FCR-D upwards is procured to the same amount as the reference incident. All FFR recovery will lead to a decrease of the system frequency, leading to a corresponding activation of FCR-D.

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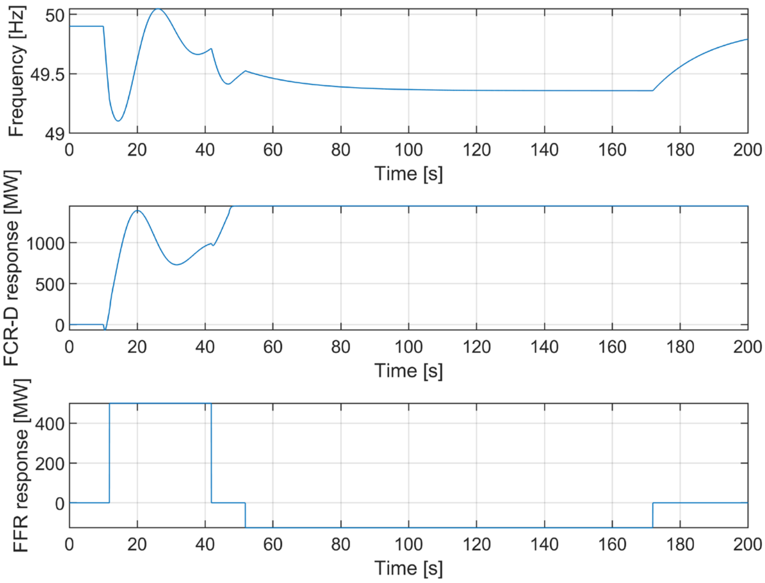

Figure 12: 500 MW FFR using a long duration of 30 s and a step wise deactivation. Recovery of 25 % of the FFR capacity starts 10 seconds after the deactivation ("negative FFR response").

Figure 12 above shows the simulation results of 500 MW FFR of long duration of 30 seconds with a recovery of 25% starting 10 seconds after deactivation. In theory it might become a problem if only FCR-D is to balance the system on a short-time basis as the FCR-D capacity would be the same as the reference incident. In practise this will not be a problem since there will be frequency dependent load and other power reserves available to mitigate the impact of the recovery. In the future it might be necessary to study this issue further. Figure 13 below shows the simulation results of 150 MW extra FCR-D upwards reserve.

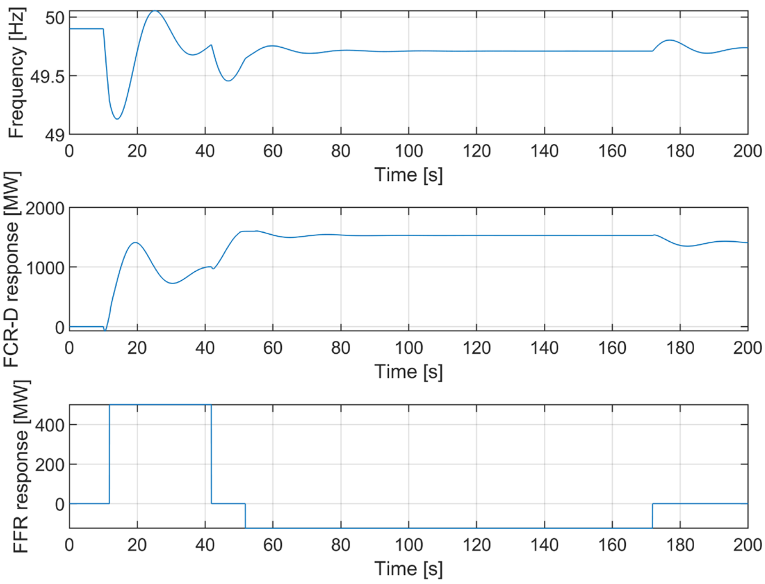

Figure 13: 500 MW FFR using a long duration of 30 s and a step wise deactivation. Recovery of 25% of the FFR capacity ("negative FFR response") starts 10 seconds after deactivation using 150 MW extra FCR-D upwards reserve.

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The extra reserve will mitigate the reduction in frequency.

5. Conclusion

This report describes the studies behind the most important FFR requirements with respect to the transient frequency stability: activation, deactivation and recovery. The considerations when designing FFR are: the undecided FCR-D upwards requirements, the fact that FFR should be of short duration and complementing FCR-D upwards, and the triggering level of the FFR.

The activation requirements are shown in Table 2, (49.7 Hz, 1.3 s; 49.6 Hz, 1.0 s; and 49.5 Hz, 0.7 s). The activation requirements were decided when making a trade-off between activation frequency and full activation time. When a longer full activation time was simulated the efficiency dropped.

Two alternatives of support duration were decided, long and short duration. The long duration is at least 30 seconds while the short duration is 5 seconds minimum. The long duration can be deactivated as a step while the short duration needs to be deactivated as a ramp with maximum 20%/s of the FFR capacity.

FFR providing entities have to wait for 10 seconds after the deactivation prior to initiating any recovery. The maximum allowed power for recovery is 25% of the FFR capacity.

It is concluded that overdelivery of FFR results in overshoot in frequency, and that a limited overdelivery of maximum around 20% would not activate EPC_{over} or a potential future FFR_{over}.

In the requirements for deactivation and recovery there are safety margins added, so the FCR-D has time to stabilize the frequency before deactivation and recovery take place. This is done to ensure transient frequency stability since the models are not fully representing all power system dynamics.

Revision index

Ver.	Significant updates	Date	Approved by
1.0	First submission	2020-03-04	RGN

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