EXTERNAL

REPORT

FCR-Design Project Summary report

v 1.0

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13 January 2019

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1. Introduction

The project "Revision of the Nordic Frequency Containment Process" (FCP-project) was conducted in 2014-2017 and aimed at developing new, Nordic harmonized, technical specifications for FCR-N/D [4]. In the FCP project the FCR-N requirements were thoroughly analysed and discussed with the stakeholders. Estimations performed on the possibility to qualify FCR-N capacity indicated that sufficient FCR-N capacity could be qualified, resulting in a satisfactory liquidity in the future FCR-N market [9].

The development of new FCR-D requirements performed in the end of the FCP project, where the design was based on the system needs, did not focus on fulfilling the market liquidity. The estimation of the possibility to qualify sufficient FCR-D capacity indicated challenges as not enough hydro FCR-D capacity could be qualified in Finland. Therefore, it was decided to start this FCR-Design project where the aim was to revise the FCR-D requirements from the FCP project. The overall goal of this revise was to relax the FCR-D requirements and thereby qualify more capacity to receive sufficient liquidity in the future FCR-D market. From the FCP project it was also suggested to perform additional studies to thoroughly evaluate the design process and the impact of the new FCR-D requirements both on the power system and on producers delivering the FCR-D service. The FCR-Design project contains the following main parts [1]:

1. Revision of the FCR-D design requirements to qualify more hydro FCR-D capacity
2. Switch-over between FCR-N and FCR-D and vice versa to secure acceptable behavior when delivering both FCR services from a hydro unit
3. Full scale simulations in PSS/E to verify that the simplified one mass Simulink model used during the project gives an acceptable behavior

The purpose with this document is to make a high-level summary of the completed work within the FCR-Design project [2], [5], [7], [8].

2. Update of the FCR-D design

In this chapter the different parts included in the update of the FCR-D design are described.

Relaxing the FCP requirements

Based on the methodology of stability and performance requirements developed in the FCP project [6] qualification of more FCR-D capacity can be done either by relaxing the stability requirement and/or relaxing the performance requirements. The relaxing of the requirements will then result in a need for another frequency control service, FFR [10], to be used when the system kinetic energy is below certain levels. Depending on how the new FFR service is designed it will have different impacts on how to relax the FCR-D requirements. It has been decided [3] that the new FFR service shall be limited in time, i.e. the dimensioning FCR-D capacity shall be 1450 MW for all levels of system kinetic energy.

Both the stability and the performance requirements are strongly related to the system kinetic energy. Principally, the stability and performance requirements can be dimensioned using the same system kinetic energy or using different kinetic energies. As stability of the system is crucial it has been decided that the relaxing of the requirements shall be on the performance requirements, i.e. the system shall fulfil the stability requirement for all expected system kinetic energies. The possible way of relaxing the performance requirements is to dimension it for a higher system kinetic energy. For lower system kinetic energies, the new FFR shall be used for keeping the frequency above 49.0 Hz and below 51.0 Hz.

Performance requirements

In the FCP project the performance requirements were divided into three parts;

- Steady state power change when exposed to a frequency step change of ±0.4 Hz
- Power and energy requirements 5 s after a frequency ramp of 0.3 Hz/s with 3 s duration is applied

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In this project the same methodology has been used but the dimensioning kinetic energy has been varied which has given a variation in the applied frequency ramp resulting in different power and energy requirements. These requirements have then been used as basis for the estimation of qualified FCR-D capacity in the Nordics at different kinetic energies. In Table 1 a summary of the requirements is presented for different kinetic energies. As the final decision of the FCR-D requirements is not made yet the dimensioning kinetic energy, power and energy requirements are not determined, i.e. it can be either of the rows given in the table.

Table 1 Power and energy requirements based on different dimensioning kinetic energies.

	Requirements		
Kinetic energy (GWs)	Time (s)	Power (pu)	Energy (pu*s)
100	5	0.93	2.3
120	6	0.93	2.8
140	7	0.93	3.3
160	8	0.93	3.9
180	9	0.93	4.4
200	10	0.93	4.9
220	11	0.93	5.4
240	13	0.93	7.0
260	14	0.93	7.5
280	15	0.93	8.0
300	16	0.93	8.6

Stability requirement

To ensure a stable frequency control in the Nordic power system a stability requirement was designed in the FCP project [6]. In this project the same stability requirement has been used as in the FCP project. The only difference is due to the kinetic energy scaling of the requirement. In the FCP project the dimensioning system kinetic energy, E_{ks}, was 120 GWs whereas in this project 90 GWs has been used. Sensitivity analyses have also been made when varying the system gain and/or changing the dimensioning system kinetic energy to study the impact on qualified FCR-D capacity.

Saturation

In the FCR-D requirements developed in the FCP project [6] it was concluded that the steady state activation of FCR-D capacity should be linearly proportional to the steady state system frequency deviation. This to make sure that the gain of the system (MW/Hz) does not exceed the dimensioning gain and thereby lower the stability margin of the system. However, based on producers request and the TSO wish to qualify more FCR-D capacity the project has analysed the possibility to accept that units saturate, i.e. delivers all their FCR-D capacity before reaching a steady state frequency deviation of 0.4 Hz. The analysis has been made using the input that the system stability shall not be deteriorated if units contributing with FCR-D are saturated.

Accepting saturation of units results in a variation of the system gain. Just below 49.9 Hz the gain will be highest and close to 49.5 Hz the gain will be lowest. To make sure that the system stability is maintained the highest gain of the unit to be qualified is considered for the stability analysis.

Capacity estimations with new requirements

To study the qualified hydro FCR-D capacity in each Nordic country as a function of the system kinetic energy many simulations have been performed where different parameters have been varied. The results of the simulations performed can be found in Figure 1-Figure 3. As can be seen in the figures not only the kinetic energy for the performance requirement has been varied. There is also a variation of the kinetic energy dimensioning the stability requirement and a variation of the maximum loading that the units are qualified for. If fulfilling the dimensioning requirements stated in [3] the following shall be valid:

- Loading of the units shall be 80 %
- Kinetic energy for dimensioning the stability requirement shall be 90 GWs
- Qualified hydro FCR-D capacity for Norway and Sweden shall be 150-200 % of the national obligation
- Qualified hydro FCR-D capacity in Finland shall be 100 % of the national obligation

The national FCR-D obligations are:

- Norway 537 MW
- Sweden 580 MW
- Finland 290 MW

In the figures below the minimum system kinetic energy fulfilling the dimensioning requirements given above are marked with a black circle. For both Norway and Sweden, it is not an issue to qualify sufficient capacity also for rather low system kinetic energies. In Finland, however, qualification of sufficient capacity is only possible when the dimensioning kinetic energy is more than 300 GWs.

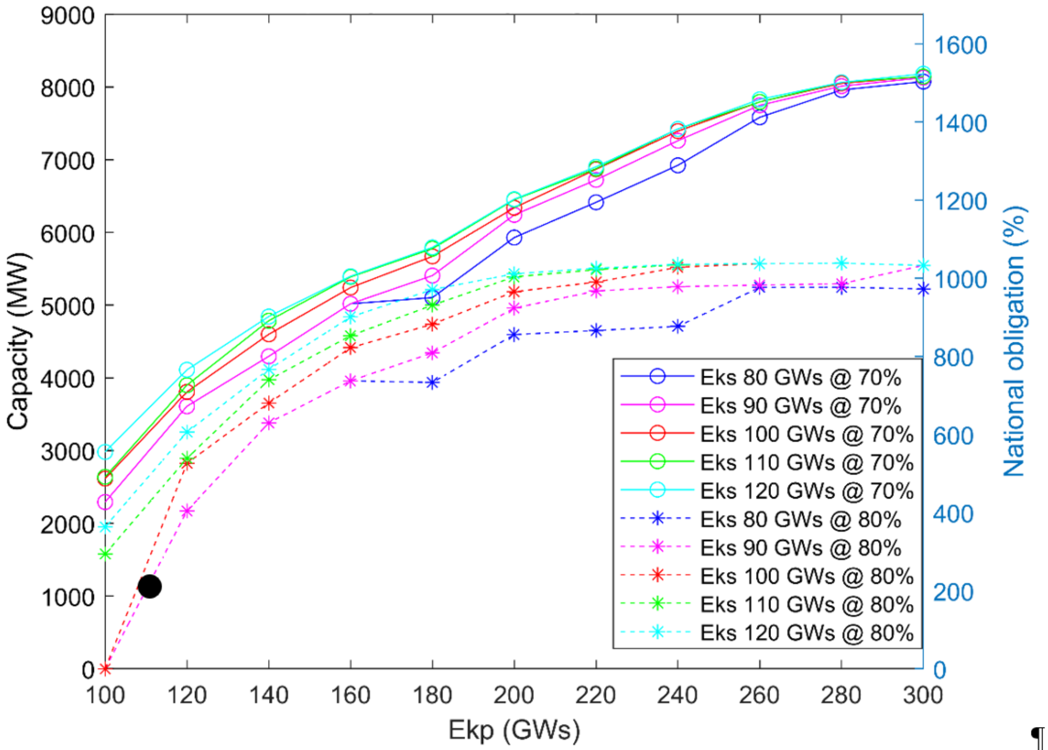

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Figure 1 Estimated FCR-D capacity in Norway, based on installed capacity and distribution of water time constant, as a function of system kinetic energy. Black circle fulfils dimensioning requirements [3].

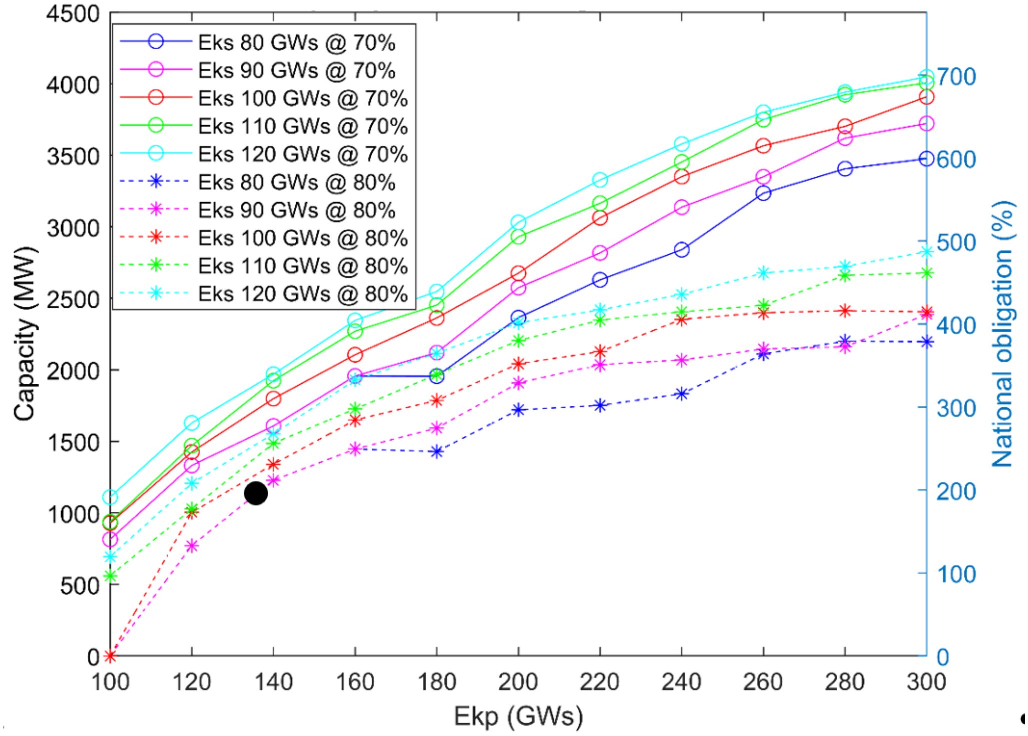

Figure 2 Estimated FCR-D capacity in Sweden, based on installed capacity and distribution of water time constant, as a function of system kinetic energy. Black circle fulfils dimensioning requirements [3].

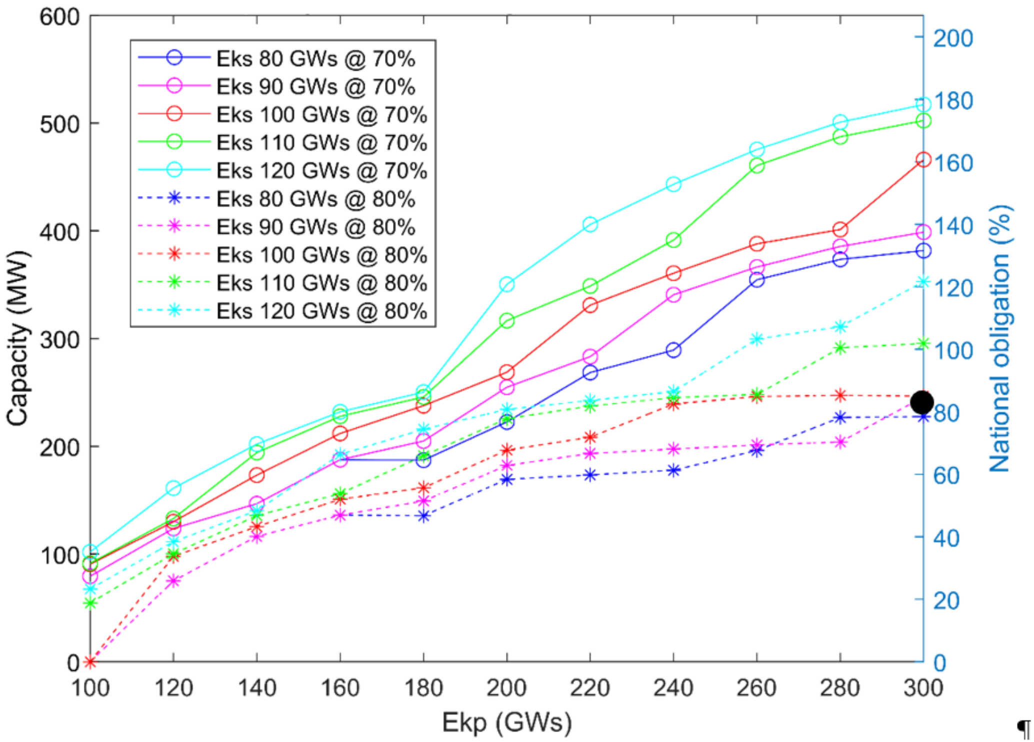

Figure 3 Estimated FCR-D capacity in Finland, based on installed capacity and distribution of water time constant, as a function of system kinetic energy. Black circle fulfils dimensioning requirements [3].

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3. Switch-over between FCR-N and FCR-D

In the present Nordic power system, most hydro units supply both FCR-N and FCR-D. As the existing requirements for FCR-N and FCR-D are different there is a motive among FCR suppliers to have different parameter settings of their governors. However, the qualification/verification of hydro units for FCR-N and FCR-D are presently not that extensive in some of the Nordic countries. To generalize this means that existing hydro units in Norway and most of the hydro units in Sweden have the same parameter setting for FCR-N and FCR-D. In Finland and partly in Sweden there are different parameter settings for FCR-N and FCR-D.

For units having different parameter settings there is generally a switch-over from one parameter setting to another. The switch-over is based on frequency level and/or frequency derivative. The governor structure is generally based on one PID governor with droop feedback where the parameters are changed. As the requirements for FCR-D are tougher and requires a faster response the parameter settings for FCR-D are generally more aggressive than the parameter settings for FCR-N. The proposed changes of requirements for FCR-N and FCR-D presented in this project and the FCP project [6] will probably result in that more units will have different parameter settings for FCR-N and FCR-D.

As the requirements for FCR-N and FCR-D are focused on their respective service it is important also to investigate the behaviour in the borders between these products, i.e. at 49.9 and 50.1 Hz, and to make sure that nothing strange will occur around these regions if units have a switch-over function. Three different scenarios have been investigated regarding the FCR-N and FCR-D:

1. FCR-N and FCR-D are supplied from different units – base case
2. FCR-N and FCR-D are supplied from the same unit but with one regulator structure (PID and droop feedback) and a change of parameter settings between FCR-N and FCR-D - the conventional way used today
3. FCR-N and FCR-D are supplied from the same units but with two parallel governor structures in the governor, one for FCR-N and one for FCR-D, and consequently no parameter change – the recommended way for future delivery of both FCR products from a unit

During the different simulations performed the impact from changes of governor parameters have been studied and compared with the base case (1) where FCR-N and FCR-D are supplied from different units. It can be concluded that a unit providing both FCR services and using a parallel governor structure (3) gets the same behaviour as if the FCR services are delivered from different units (1).

If the unit delivers both FCR services but only has one governor structure (2) the behaviour will differ as compared to the other scenarios. If having different droops settings for FCR-N and FCR-D it can already from a comparison of the steady state behaviour in Figure 4 and Figure 5 be seen that there will be a non-tolerable difference in the behaviour. Simulations performed [2] also show that the dynamic behaviour will differ in a non-tolerable way. Therefore, it is concluded that it is not accepted to change the droop setting if using a single governor structure with parameter change.

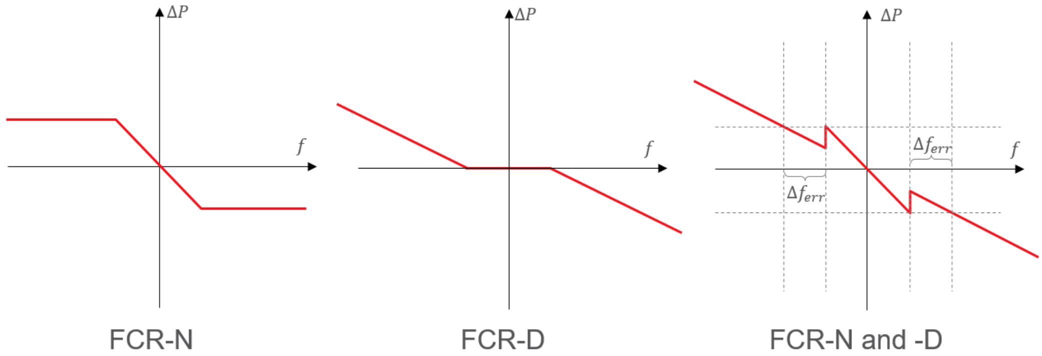

Figure 4 Steady state relationship between power change, ΔP, and frequency, f, of a conventional governor (2) with switching of droop at 49.9/50.1 Hz ($\boldsymbol{droop_{FCR-N}} < \boldsymbol{droop_{FCR-D}}$)

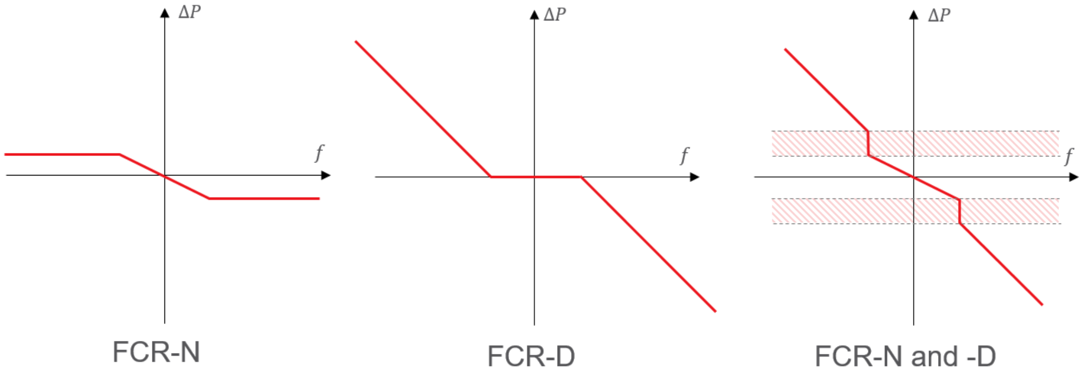

Figure 5 Steady state relationship between power change, ΔP, and frequency, f, of a conventional regulator (2) with switching of droop at 49.9/50.1 Hz ($\boldsymbol{droop_{FCR-N}} > \boldsymbol{droop_{FCR-D}}$).

Parameter changes of the other governor parameters such as proportional part, integral part and derivate part also give a variation of the system behaviour as compared to if the FCR services are delivered from different units. In Figure 6 a comparison is shown when the proportional part deviates between the FCR-N and FCR-D. In the brown curve the products are delivered from different units whereas in the blue curve they are delivered from the same unit having a parameter change. As can be seen there is a rather small variation in the behaviour. Also, when studying the impact on a parameter change on the integral and derivative part there is a small variation in the behaviour. However, the project has concluded that the change does not have a severe impact on the system behaviour. Therefore, to make it easier for producers to use existing governors it is recommended to accept parameter change in the conventional way for proportional, integrating and derivative parts in the governor.

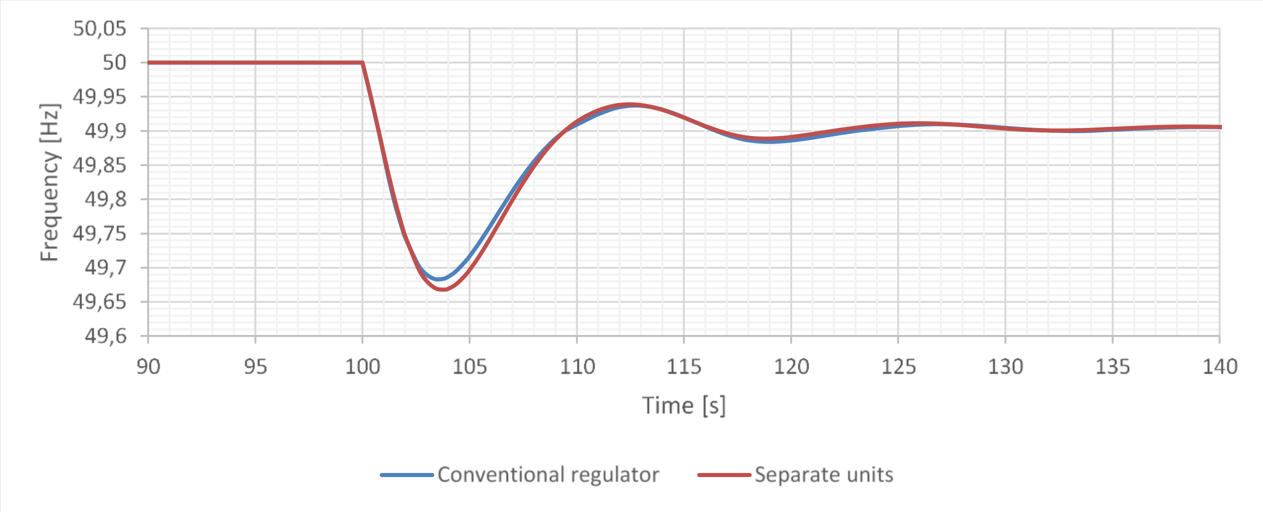

Figure 6 Comparison of the dynamic system behaviour after a 600 MW unit trip when using different units for supplying the FCR services (brown) and when using FCR services from the same units using, $K_{P,\ FCR\text{-}N}$=4.4 and $K_{P,\ FCR\text{-}D}$=10.4.

4. Full scale simulations in PSS/E

As described in chapter 2 and in [6] the technical requirements for FCR-D have been developed using a simplified lumped one mass model, a lumped production model and a lumped load model. Therefore, it is important to ensure that the system behaves in an expected way also when performing similar simulations in a larger system with other types of dynamics included [1].

When performing and comparing simulation results of the lumped one mass model with the full-scale simulations focus has been on studying the frequency nadir, i.e. the lowest frequency after a loss of production, and the stability, i.e. the damping of the frequency oscillations after a disturbance. Simulations have been performed using three different disturbances, two different load flows, two different governor settings and by activating/deactivating different dynamics in the full-scale simulation model.

Simulations in the PSS/E model and the simplified Simulink model, see example in Figure 7, show that it is acceptable to use the simplified Simulink model as it gives roughly the same behaviour as the PSS/E model. The differences that occur are also conservative, i.e. the PSS/E model including more models and dynamics gives a better response as compared to the simplified Simulink model.

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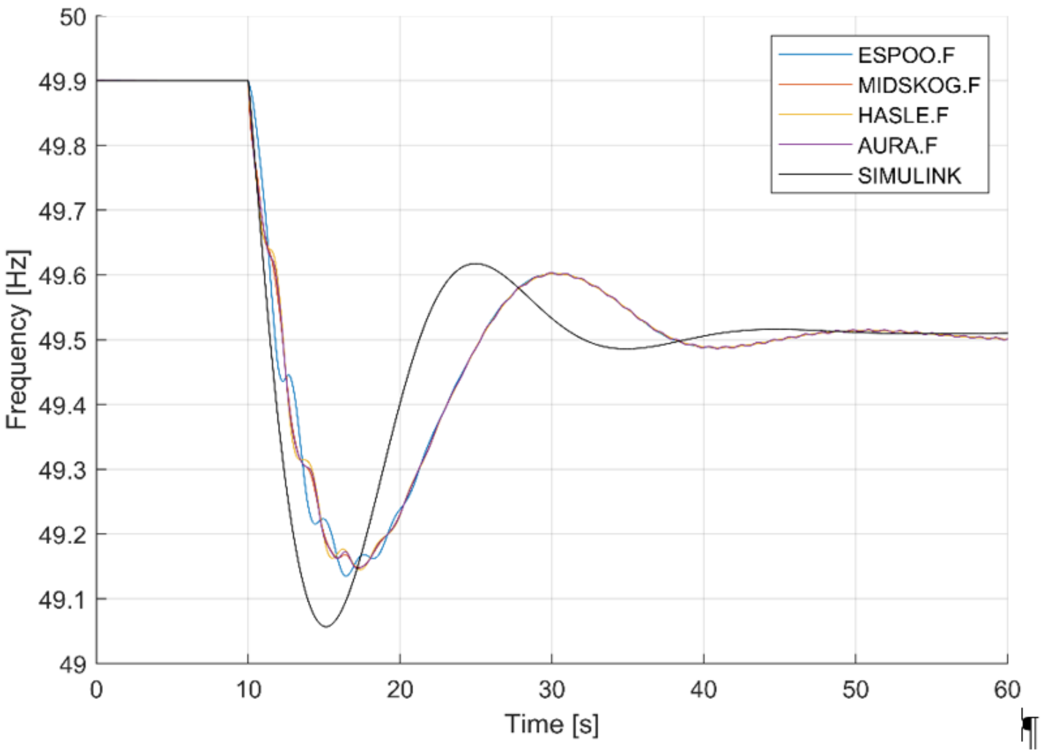

Figure 7 Frequency response comparison between simulations performed using the simplified Simulink model and the PSS/E model after a trip of 1450 MWproduction, PSS/E model includes all the specified dynamic models.

5. Main and supporting prequalification documentation

In the FCP project, the technical requirements for FCR-N and FCR-D were described in the main document [7] and further explained in the supporting document [8]. In this project the focus has been on the FCR-D whereas the FCR-N requirements have been kept unchanged. As described in chapter 2 the principles for deriving the FCR-D requirements are the same in this project and the FCP project. This means that the FCR-D requirements are based on both a stability requirement and performance requirements that are tested on unit base. Due to changed input to the project [3] the dimensioning of FCR-D requirements will be changed. However, as the final input is not decided yet the final requirements cannot be stated in this project. Already before the decision is made it can, however, be concluded that there will be a change of the dimensioning kinetic energy for the performance requirements which will result in a change of the test signal used for checking fulfilment of the performance requirements. Because of this also the power and energy requirements will be changed. As the input for dimensioning of the stability requirement is changed this results in a change of how the Nyquist curve is calculated and scaled. The change of the scaling of the Nyquist curve now also includes the acceptance of saturation on units delivering FCR-D as described in chapter 2.

As already concluded in the FCP project [5] the active power response will not be the same for a unit using active power feedback in the governor during a test, when the grid frequency is constant, as compared to a real situation, when the grid frequency varies. Therefore, the main and supporting documents have been complemented with requirements for units using active power as feedback signal in the governor.

The investigation of the switch-over between FCR-N and FCR-D, described in chapter 2 show that it is possible to accept the conventional changeover of parameter settings under certain conditions. These conditions together with a new suggested test will be added to the main and supporting documents. In the supporting document, also a recommendation is made to complement the governor with parallel regulators for FCR-N and FCR-D to reduce the negative impact on the wear and tear when changing parameters.

6. Conclusions and discussion

The update of the FCR-D requirements performed in this FCR-Design project has basically been made using the same methodology as developed in the FCP project. The overall goal of this project has been to relax the FCR-D requirements developed in the FCP project to qualify sufficient hydro FCR-D capacity in all Nordic countries. The development of the requirements was made using a simplified one mass model in Simulink. Data from previously performed surveys has been used to give realistic parameter settings and distribution of parameters for the hydro units. The development of the requirements has been based on realistic data and assumptions. Some assumptions may be considered as conservative whereas other may be rather non-conservative. In total, it is the working group's opinion that the developed requirements are based on reasonable assumptions and therefore it is not recommended to operate the system outside the ranges used when developing the requirements.

Full scale simulations performed in PSS/E, using the full Nordic model including all production units and dynamic models, show a behaviour that is slightly better than the behaviour received when using the simplified Simulink model. This confirms that it is acceptable to use the simplified Simulink model for the development of the new FRC-D requirements.

The need for system kinetic energy to qualify requested FCR-D capacity using the given dimensioning requirements is roughly 300 GWs and this would require the use of the new FFR service during a large part of the time to ensure system transient frequency stability. This is most probably not an acceptable solution. Therefore, the final choice will be a trade-off between the qualified capacity from hydro power units in Finland and the needed FFR volume

In the FCR-D capacity studies made, the large impact of the unit water time constant and loading of the unit have been demonstrated. Prequalification of capacity for a lower loading would significantly increase the qualified capacity. However, it is reasonable to assume that producers will prioritize the delivery of energy and therefore qualification for FCR-D will be based on typical operating ranges of the unit. A reduction of the water time constant is not realistic to make either, as this would require an increase of the tunnel area.

As can be seen from the studies on qualification of FCR-D capacity this is a challenge linked purely to Finland and consequently, solutions to the capacity challenge is strongly related to a solution of the Finnish situation. Already today Finland purchases parts of their FCR-D capacity from other sources than hydro. Therefore, this has already been considered as the dimensioning is based on that only 100 % FCR-D capacity from hydro units shall be qualified in Finland. If a further reduction of the Finnish FCR-D capacity from hydro could be made, either by having more FCR-D from other sources or by accepting that Finland buys FCR-D capacity from Sweden or Norway, the dimensioning system kinetic energy could be significantly reduced giving a more realistic solution, ensuring a FCR-D handling N-1 with a reasonable amount of FFR.

In the FCP project the development of the FCR-N requirements were thoroughly communicated with the stakeholders through several reference group meetings. Some proof of concept tests were also performed and together with previously performed tests the working group had a rather good understanding for the limitations when running in FCR-N mode. In this project there has been no reference group and no proof of concept tests as the project mainly was about to re-tune the requirements developed in the FCP-project, which was considered possible without engaging a large reference group.

Further on, the FCR-Design project deliveries will be followed up with a Nordic feasibility / CBA evaluation on implementation. After these evaluations, it is the aim to set a recommendation for technical requirements and by that update the project documentation.

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