FCP Project Summary report

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1. Introduction

1.1. Background

In the end of 2010 the "RAR-project" was started up, with the aim to provide a basic recommendation on requirements for automatic reserves, including technical requirements for automatic secondary reserves. In this work, the slow frequency oscillations in the Nordic system was highlighted as a significant contributor to frequency quality deterioration. Therefore, RGN decided to launch the "60s project" as a project to find the reasons for these oscillations, together with identifying possible measures to reduce the frequency oscillations. This would then also be a measure to reduce the wear and tear of production units that had been brought up as an issue by certain producers.

The 60s project was running in two different phases until 2014. The summary conclusion from the work was that the reason behind the oscillations was a result of system properties coming from power imbalances in the system, and also hydro power configuration that doesn't contribute with dampening of oscillations. In addition to this, the size of the system and the production composition plays a major role. The work also revealed the fact that there are large differences between how the Nordic countries, and producers within each country, have interpreted the current SOA FCR requirements and if/and in what way pre-qualifications are being performed.

The project "Revision of the Nordic Frequency Containment Project" (FCP-project) was initiated in the very end of 2014, and had the aim to 1) create new, Nordic harmonized, technical specifications for FCR-N/D and 2) define an implementation plan for transition from current to new FCR. The project would run for 1,5 years and consist of TSO project working members, reference group meetings with members from producers, manufacturers and universities, and an external project manager.

During the project, a number of issues have been identified. Creating an FCR robust for all inertia variations, mechanical backlash issues, potentially much larger compared with original knowledge, a present FCR-D requirement far from present system need, etc. The summary of these challenges has in the end more or less changed the project from a "simple" optimization problem to something more like an RnD project.

1.2. Aim

The aim with the following document is to make a high level summary of the complete work that has been performed within the project. This work has mainly been performed within the three working groups "Control Design", "Pre-qualification" and "External communication".

2. Constraints

The constraints [1] for the project constitutes of foremost the technical requirements coming from the existing and coming Entso-E technical requirements and the system operation guidelines. The constraints are divided into e.g. frequency quality requirements, frequency response requirements, governor/turbine/station parameters, and especially system parameters for which the FCR-N shall be able to fulfil the requirements. These system parameters cover maximum, nominal and minimum production levels and kinetic energy, together with load frequency dependency (system inherent damping), parameters that are crucial for defining the requirements.

The constrains also highlight the human and economic constraints that is a fact coming from the work defining new requirements. However, these doesn't impose a clear, limiting requirements in the work, but more point at relevant aspects to consider when looking at the impact of the new requirements.

The constraints are used when defining the methodology for the FCR-N and –D requirements (see chapter 3 and chapter 4.1), as well as the in the pre-qualification/parameter sensitivity studies.

3. Requirements for FCR-N

In the following chapter a summary of the methodology for how the requirement has been created is presented, together with results from non-linear studies that evaluate the effect on the frequency quality, together with the feasibility of requirements for existing Nordic hydro power units.

On a high level the requirements have been developed according to the following approach:

1. Use of a linear, simplified model (single lumped machine) to define the transfer function between imposed imbalance [2] to frequency output, in the frequency domain [3].
2. Applying hard and soft tuning goals across the frequency range and optimizing the single machine model against this [3].
3. Studying the non-linear effects in a non-linear model [5], sweeping critical parameters like droop setting, governors settings (Kp, Ti), water way time constants, to study the feasibility of the requirements set by via the linear model [6-8].
4. Full scale simulations to verify the system behaviour seen in the simplified model [11]

Step 2 in the above list only had the purpose of deriving a set or reasonable optimal parameter sets used as default parameters in full scale studies (point 4).

3.1. Methodology

From the very beginning of the project the aim was to perform careful analyses including modelling of both hydro, thermal, wind and loads. However, insight along the road revealed that there already are large challenges to understand the full details of hydro power. Based on this, and the fact that approximately 90 % of all FCR in the system per today is delivered by hydro, there was a clear understanding that the study needed to focus on hydro in first place. However, with reference group members from thermal plants as well as industries, the project could as far as possible get input from these stakeholders regarding feasibility of the new requirements.

The methodology for defining new FCR-requirements has been taking a simplified model for an FCR providing unit and a grid (one mass model) as starting point studying the effects of different imbalances vs FCR behaviour and system (grid) properties, see Figure 1. In the methodology, the *system needs* have been used as a basis, and. This means that frequency quality limits, needed stability margins for forecasted future variations in inertia etc. have been identified and used in the dimensioning. Real imbalances [2] have also been used as a basis for the requirements set forth.

The FCR-N and –D requirements have gone from the very simple "activation time and volume", as specified in the SOA per today[1], to a requirement based on

1. performance and
2. stability.

[1] The existing Nordic requirements for FCR-N is that 100% of the steady state capacity shall be activated within 2-3 minutes. This requirement can be seen as a performance requirement.

The performance requirement is a basically specifying that the amplitude of an imbalance is to be reduced to a certain size, while the stability requirement make sure that the power system is stable and does not start to oscillate. The requirements for FCR-N and –D is in this sense in practice the same, but the imbalance to be taken care of, differ between the two products. Performance requirements are evaluated for the nominal system and the stability requirement is evaluated for the worst-case system.

Stability requirement is a new side of the FCR-requirements, both seen from current requirements in SOA and also seen from what is specified in the Entso-E System operation guideline. However, historically stability has been the core for the Norwegian requirements, and the derived requirement in the FCP project is somewhat close to the Norwegian way of setting the stability requirements.

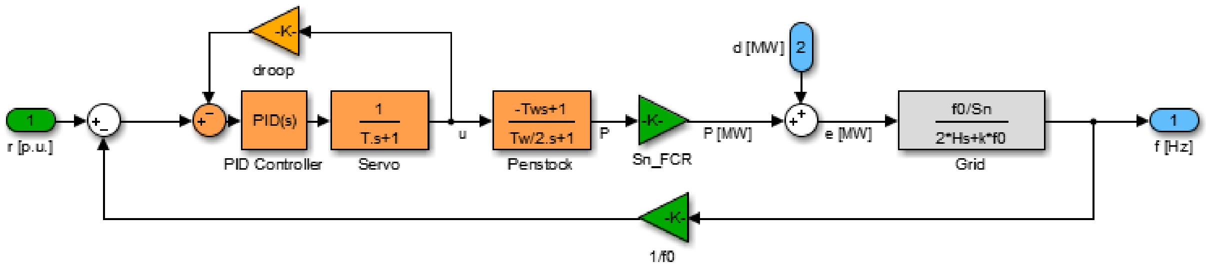

Figure 1 Simple single machine- single system model used.

3.2. Imbalance study

Real imbalances in the system have been measured and used [2] to define the needed properties of the new FCR, both in terms of performance and capacity. An approximate steady state capacity of 600 MW seems reasonable, but it's also clear that the needed capacity will be different for different operational scenarios. From the imbalance study, it also becomes clear that the imbalance varies with the period time. For shorter period times the imbalance is less than for longer period times. The imbalance can be seen as white noise feeding a filter estimated as

$$D = \frac{600}{(1 + s36)}$$

3.3. Pre-qualification study and parameter sensitivity study

When defining requirements, there has been a trade-off between improvement of frequency quality and feasible requirements for Nordic hydro power production units, i.e. a very strict requirement implies good potential in improvement of frequency quality, but a requirement that can be rather hard to fulfil and thereby creating challenges for getting a well-functioning FCR-market. The process has thereby been iterative between system performance and unit qualification feasibility.

One of the key parameters is the backlash of the units that has shown to have a significant impact on the possibility to fulfil the requirements and the flexibility in parameter tuning of the turbine governors. Generally, the higher the backlash becomes the tougher it becomes to find governor parameters that fulfil the requirements. An example of this can be found in Table 1 where the black lines show which droop settings that must be used for qualifying at different backlash values.

The requirements on performance and stability will clearly improve frequency quality in the terms of reduced "minutes outside normal operating band" (MoNB). This can clearly be seen when comparing results from Table 1 and

Table 2. If assuming an average backlash of ± 0.5 % in the system, the MoNB is reduced from almost 40 000 to roughly 15000 minutes[2].

In Table 1 it is clear that the area of operation, in order to be pre-qualified for new requirements, will be limited when it comes to possible droop settings. The higher the mechanical backlash, the lower droop setting will be possible.

In the evaluation of the requirements [8], there are also clear indications that the amount of work (movement of mechanical parts) for an FCR providing unit will be reduced, which is assumed to be a clear indication that the wear and tear will be reduced. Implementation of the new requirements can therefore be a win-win situation between the TSOs and the producers. However, the reduced work will only be "visible" when all FCR providing units will be pre-qualified, and hence the frequency quality has been improved.

Table 1 Simulated MoNB when using different backlash and droop setting values [8]. Optimized parameter settings used for the PI part in the governor [3]. Area encircled by the black lines are qualified units [7]. Other parameter settings can also result in qualification for higher backlash values.

MoNB Droop\BL	0	0,001	0,002	0,003	0,004	0,005	0,006	0,007	0,008	0,009	0,01	0,011	0,012
0,02	8863	9656	10755	12230	14115	15874	17501	19395	21223	23633	25587	27728	29900
0,04	7645	7762	8316	9337	11083	13621	16192	18546	21684	24637	27837	31345	33967
0,06	7515	7944	8363	10913	13746	17594	22464	27113	30745	35712	39643	46185	50998
0,08	7515	7817	10155	13801	19260	25125	30630	37583	43917	50194	60203	65423	71955
0,1	7515	8113	11917	17899	24961	32666	41578	50651	58478	69706	79398	97799	110267
0,12	7515	8362	13923	22487	31836	40061	52048	62509	75727	89934	112880	122228	137987

Table 2 Simulated MoNB when using different backlash values [8]. Base case parameters used for the Nordic power system anno 2017 [5].

BL	0	0,001	0,002	0,003	0,004	0,005	0,006	0,007	0,008	0,009	0,01	0,011	0,012
MoNB	7176	13295	20707	27868	33971	39743	44922	51258	56915	64132	68397	72991	78303

Looking at the system performance when also including aFRR, it has been shown that that the optimal solution in terms of frequency quality is approximately a 50/50 solution between FCR-N and aFRR . However, there has also been seen that even further optimization regarding frequency quality can be performed if also tuning the aFRR product together with the FCR-N [9].

3.1. Comparison with existing requirement

The proposed FCR-N requirements have changed rather much as compared to the existing SOA [17] requirements anno 2017. One of the fundamental differences between the existing and the new requirements is the introduction of a stability requirement, which to some extent is close to the existing requirement in the Norwegian grid code.

4. Requirement for FCR-D

4.1. Methodology

[2] Note, it is foremost the relative change that is of interest. A Nordic default value of 40000 minutes is a result of modelling and assumptions of imbalance profile.

The new FCR-D requirements are based on the power system need. In the same way, as for FCR-N this means stability and performance requirements. The performance requirements are divided into a steady state requirement and two dynamic requirements.

- The steady state requirement is stating that all FCR-D capacity shall be activated if the steady state frequency is below 49.5 Hz or above 50.5 Hz.
- The dynamic requirements are related to the system requirement that the frequency is not allowed to go below 49.0 Hz or above 51.0 Hz due to a trip of 1450 MW production/load.

The dynamic requirements are further divided into a power and an energy requirement after applying a frequency derivative of ± 0.3 Hz/s during 3 seconds, i.e. from 49.9 Hz down to 49.0 Hz or from 50.1 Hz up to 51.0 Hz. The power and energy are measured 5 s after the frequency derivative is started. The lowest capacity achieved from the three requirements give the capacity that can be sold to the market. The relationship with the steady state capacity and the dynamic capacity gives a correction factor that is used to scale the system strength (MW/Hz) in the stability requirements. Except for this scaling factor, the stability requirements are the same for FCR-D and FCR-N and they are also tested in the same way.

4.2. Pre-qualification study and parameter sensitivity study

The studies performed show that there are different parameters of a production unit and the turbine governor settings that affect the possibility to comply with the requirements. For hydro units, it is generally the dynamic requirements that are the toughest to fulfil. Generally, it can be stated that it becomes more difficult to fulfil the requirements if having a high water time constant, T_w, combined with a high loading of the unit. If having a higher droop setting of the unit, it becomes easier to fulfil the requirements. This is in contrast with the FCR-N where the opposite behaviour could be seen, i.e. it becomes easier to qualify if the droop setting is low. Therefore, it is likely that it will be difficult to find a common parameter setting that fulfils both the FCR-N and FCR-D requirements.

4.3. Comparison with existing requirements

The proposed FCR-D requirements have changed rather much as compared to the existing requirements anno 2017. The new requirements are symmetrical which means that they are valid also for over frequency and not just under frequency that the existing requirements are covering. The new requirements are strongly related to the power system need of both stability and performance. This can be compared with the existing performance requirement that is only stating a performance requirement after 5 s and 30 s respectively. Also, the test procedure for the dynamic requirements, with a frequency derivative of ± 0.3 Hz/s, together with the need of power balance after 5 s are closely related to how it will be in a real dimensioning situation.

4.4. "Switch over" between FCR-N and FCR-D

In the simplest form, FCR-N shall be activated within 49.9 and 50.1 Hz, and FCR-D between 49.9 and 49.5 Hz (and 50.1-50.5 upwards). This means that FCR-D shall be activated whenever frequency drops below 49.9 Hz.

There is a clear understanding that, with present frequency variations, FCR-D will be frequently activated with such a simple criteria. If a units has different parameters sets up for FCR-N and –D, this could potentially result in a large number of "switch over" situations between FCR-N and –D, which also is seen as a potential risk for increased wear and tear, transients in FCR providing units, as well as increased non-linearities in the system.

In order to reduce these negative effectsother suitable activation criteria for FCR-D needs to be evaluated.

5. Power vs guide vane feedback

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The turbine governor of a production unit use the grid frequency as an input signal but also measure the production of the unit as a feedback signal. Historically the governor feedback signal in a hydro unit has been based on the guide vane opening or the servo position and today this is the most commonly used feedback signal among production units in Sweden and Norway. In Finland, however, all units participating in the FCR market are today using active power as feedback signal in the turbine governor.

There are some major differences between guide vane feedback and power feedback control.

- Due to the non-linear relationship between the guide vane opening and the active power production of a unit, the delivered MW/Hz will vary significantly with the loading for a unit using guide vane opening as feedback signal, whereas it will be constant for a unit using power as feedback signal in the turbine governor. In [13] this MW/Hz variation was referred to as “incremental gain” and it was shown that it could vary as much as a factor of 3-4 between low and high loading for a unit having guide vane as feedback signal.
- Due to the delay in the waterways, including the non-minimum phase phenomena[3], the feedback signal will be delayed if taken from the active power as compared to the guide vane opening/servo position.
- For a unit having large backlash the change of guide vane position can result in no change of the power production. If a governor is using guide vane as feedback signal, a frequency change can therefore, due to the backlash, result in a situation where there will be no change in the active power output from the unut. If the unit, however, is using active power as feedback signal, there will be a change in active power after a frequency change. The use of active power can then in a simplified way be described as a backlash eliminator.
- The proposed testing of a unit when synchronized to the main grid is performed when the grid frequency/frequency derivative is almost constant. Therefore, the change of the unit kinetic energy is negligible during these tests. In a real situation, however, the frequency/frequency derivative will result in a change of the kinetic energy of the unit. As a change of the kinetic energy will be measured as a change of the electric power produced, this will be captured by a units using active power as feedback signal. For a unit using guide vane feedback, this change of active power output due to change of kinetic energy will not be detected, and thus the total response will constitute of kinetic energy transferred, as well as power due to increased mechanical power due to governor action.

  In the project, it has been decided that units selling FCR products are not allowed to make credit of the change of kinetic energy to fulfil the requirements, i.e. the kinetic energy of production units belong to the power system. This has then created a need of a modified test setup for these kind of units, see Chapter 6.

6. Pre-qualification specification

Looking at the pre-qualification procedures per today, the FCR-N requirements iare strictly followed in Finland and verified at tests at highest and lowest loading where FCR-N shall be sold. In Sweden, a test is also required but the producer can perform the test at any load level. In Norway tests are normally not conducted to verify FCR-N. In Norway, there is a requirement that a production unit shall be dimensioned for island operation and this requires that the unit has appropriate stability margins. The margins are expressed as phase and amplitude margins in an islanded system.

[3] Basically results in power output in wrong direction compared with the triggered need from frequency measurement and governor action.

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As discovered in [13] the unit MW/Hz can vary with a factor of 3-4 between different loadings (defined as incremental gain) for units having guide vane as feedback signal in the turbine governor. Therefore, it is important to consider the real MW/Hz at the unit point of operation. Otherwise, it is possible to perform the frequency step-response test at the loading point where the highest MW/Hz is achieved. Then there is a risk that there will not be enough MW/Hz and capacity in the system and that producers are not paid for what they deliver. Except loading, the water head of the unit also affects the delivered MW/Hz and capacity.

As found out in [14], the backlash of hydro units is significantly higher than expected. The impact of the backlash also varies depending on the previous power change. If continuing the power change in the same direction as before there will be no impact from backlash whereas the impact will be big if changing the power direction. Today, when nothing is specified how the test shall be performed, it is therefore possible to optimize the frequency step response test to avoid the effects of backlash.

The above mentioned factors, has contributed to the forming of pre-qualification procedures as specified in [18] and [19].

In order to make it possible to test units using power as feedback signal (see Chapter 5), a modified test procedure has been developed. For FCR-N the applied tests will be the same as for units using guide vane feedback. However, the measured amplitude and phase shift from the sine in sine out tests will be corrected. For FCR-D the correction will be on the applied frequency ramp signal.

The correction factors (FCR-N) and size of the step (FCR-D) will be individual for all units. Generally, the correction factors will have the biggest impact on shorter time periods and when having low droop settings and/or low inertia time constants.

When testing the stability of FCR-D with sine in sine out tests, the same correction shall be made as when testing the sine in sine out for FCR-N.

As the modification of the test signal also might be affected by the governor structure there is a need to study this in more detail in future work.

7. Full scale verification

The development of the new requirements and the analysis performed are based on the assumption that a simplified lumped model of the power system can be used [5]. In this model, many simplifications are made and therefore it is important to verify that similar behaviour also will be found when doing simulations in a full-scale Nordic PSS/E model.

A base case with situation anno 2017 has been implemented together with a new case where optimized FCR-N parameter settings have been used. Simulations have been performed when injecting sinusoidal power variations with different period times into the model. The results of these simulations, se example in Figure 2, show that the new optimized parameter settings of the governors will supress the amplitude of the “60 s” oscillations significantly [11]. This agrees with the results found in simulations performed on the simplified model [6]. Simulations also indicate that the load voltage dependency have some positive impact on the results.

Based on the simulations performed it is not possible to find any major differences with the FCR-N results found in the simplified lumped model and the results found in the full-scale Nordic PSS/E model.

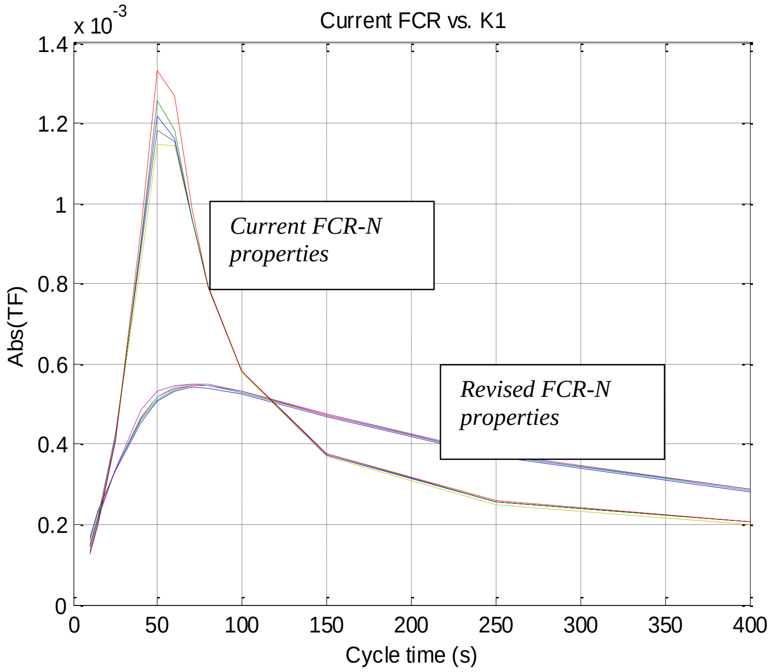

Figure 2 Power system amplification (frequency amplitude/power amplitude, Hz/MW) when injecting a sinusoidal power variation at different power amplitudes in the power system at different period times. Current FCR-N properties vs optimized parameter sets.

Full scale simulation to verify FCR-D might be even more interesting. Due to limitation in time within the project these simulations have been moved to future work.

8. Challenges and capacity evaluation

Some important, country wise, challenges have been identified. New requirements will be hard to fulfil for certain units with a special physical construction in for instance water ways, but also for units having too large mechanical backlash. In Table 1 it is shown how units with mechanical backlash above 0,01 pu will face a challenging prequalification [7].

This is foreseen to be a challenge for parts of the installed capacity in Finland, as well as some in Sweden, due to the foreseen larger backlash values and larger water time constants among Kaplan units (turbine type most common in Sweden/Finland, see Figure 3) [14]. For these units, there is no reasonable "adoption" for fulfilling the requirements, at least when it comes to water way construction. Reduction of backlash can be done by (foremost) mechanical upgrades.

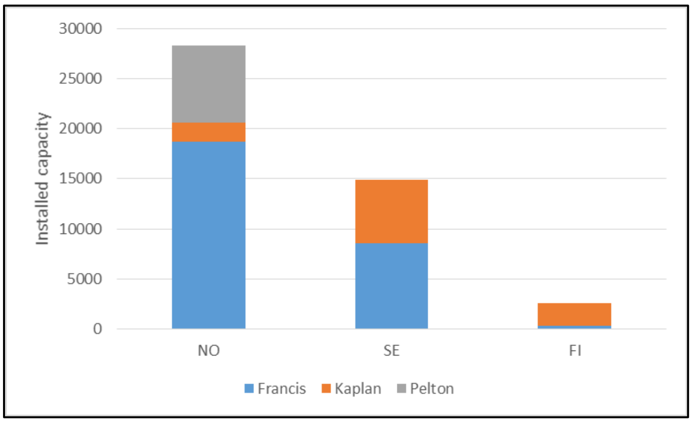

Figure 3 Distribution of installed capacity in Nordics. Data from [14].

Less challenge seen from this aspect is assumed to be the case for Norway. In Norway however, there is a fundamental need for change of the philosophy for securing island operation. In Denmark, with foremost thermal power, it is still a bit of a question mark how the requirements will be fulfilled. Indications from reference group members show a reduced FCR potential, both for FCR-N/D. The implementation phase to follow needs to monitor the feasibility of the requirements, and where necessary, adjust requirements to get a balance between fulfilment and system performance.

Table 1 Power plant qualification [7].

70 s	LF = 0.5 %												
Droop\BL	0	0,001	0,002	0,003	0,004	0,005	0,006	0,007	0,008	0,009	0,01	0,011	0,012
2%	38	34	29	24	20	13	11	8	5	2	0	0	0
4%	50	45	42	32	27	20	15	11	6	2	1	0	0
6%	56	50	25	16	15	6	5	2	0	0	0	0	0
8%	68	53	16	13	5	3	1	0	0	0	0	0	0
10%	77	53	8	6	4	0	0	0	0	0	0	0	0
12%	80	51	9	3	0	0	0	0	0	0	0	0	0

In summary, based on the assumed water time constant and backlash values among the installed units, an estimated FCR-N capacity of approximately 7 GW. In this estimation, the complete installed capacity of 45 GW (sum of units with rated apparent power > 10 MVA) has been assumed be able to provide frequency control. [12]

For FCR-D, one of the major contributors to reduced capacity due to new requirements is the fact that only a portion of the steady state power will be acknowledged as FCR-D capacity. The size of portion is droop setting depending. Another factor that significantly will contribute to a reduced capacity is high water time constants. From the studies performed it is clear that units with a water time constant above 1.8 s will not be able to be pre-qualified for FCR-D requirements [4].

From these findings, it has been concluded that there is a need to revise the proposed requirements in the next phase of the project. Different options can be evaluated for making the FCR-D requirements less harsh [4]:

- The minimum system kinetic energy can be raised, which will make the stability and performance requirements easier to fulfil
- A 'blocking time function' can be introduced, which let the FCR-D response have less stability margins for the first 10-20 seconds, after which stabile parameters are being activated. This opens up for improved performance during the critical part of the system response.

- The FCR-D requirement stating that the minimum frequency is not allowed to go below 49.0 Hz can be reduced to a lower value. This will make it easier for units to fulfil the requirements.

9. Proof of concept testing

During the project, simplified models of the production units have been used to check the prequalification capability. In real life, however, there are much more to take into consideration. Therefore, it is important to perform proof of concept testing to include all parts. Proof of concept tests are also of importance to check that the prequalification procedure can be made in a good way.

During the project six proof of concept tests have been performed, two on high head Francis turbines in Norway, two on Kaplan turbines in Finland and two on Kaplan turbines in Sweden.

From the tests, it can be concluded that it takes 1-2 days to perform the entire test procedure and if tuning shall be done it takes additional time. There has been no problem to connect and perform the tests. For the FCR-D tests, on units having power feedback control, the modified tests sequence could not be performed with the used test equipment. This can, however, be fixed by changing the software in the test equipment.

The tests on the Norwegian units started with existing parameter settings at different droop settings, i.e. in the way that is used today. The results showed that with these settings the units are far from fulfilling the new FCR-N requirements. It also demonstrated that it will not be possible to change the capacity only be changing the droop setting keeping the other governor parameters constant. This means that if different capacities shall be sold from a unit it will most likely require the governor to have different predefined modes.

After tuning the Norwegian governors, the performance become much better and the units almost fulfilled the requirements. It is likely that additional tuning on these units will make it possible to fulfil the FCR-N requirements.

The tests performed in Finland on two Kaplan units resulted in two unit that was not fulfilling the FCR-N requirements. For both these tested units, the margins to fulfil were very low. It was also shown that the loading of the unit has a rather big impact on the results. Tuned parameter settings for one load level might not be ok for another load level and vice versa. In Finland, a third Kaplan unit was also tested but already after some test sequences it was seen that there were some problems with the runner control and it was no idea to continue the tests as it was no chance to get the unit qualified.

The tests performed in Sweden resulted in one unit that was qualified for FCR-N and one unit that was not qualified. The qualified unit was recently refurbished whereas the other was rather old.

The FCR-D requirements have been tested on the two Finnish Kaplan units and on one of the Swedish units. The results from these tests show that the dynamic performance requirements reduce the qualified capacity much and only a fraction of the capacity that today is sold might be sold in future with the new FCR-D requirements. It can also be concluded that the tested units have problems to fulfil the stability requirements.

10. Market report, cost-benefit analysis

Within the project, there has been developed two reports with more market/economical focus:

- Nordic Market Report [15]

  The report specifies how the markets in each country works, both for FCR-N and –D. The report is creating a solid basis for an implementation project (next phase of the project), especially if a Nordic common market will be a part of such an implementation project.

- CBA (Cost Benefit Analysis) [16]

The report defines the principles for how to perform a cost benefit analysis as a supporting tool when deciding upon different implementation alternatives.

11. Conclusions

The work has resulted in new, harmonized requirements for FCR-N and -D, as well as a new harmonized pre-qualification procedure which is developed and tuned against the system needs. Trade-offs have been necessary in order to acknowledge the physical limitations in, foremost, the Nordic hydro power park. This means that an iteration between the level of performance of FCR providers and the frequency quality level has been done.

The project is confident in that it has created solid requirements that will be robust for the coming years and the corresponding development of the system that will take place during these years. However, it has been clear that it is a challenge to both create a solid and robust requirement, which at the same time is easy to understand and easy to get pre-qualified for.

In order to handle both a large reduction in FCR capacity, as well as getting a more sophisticated activation of FCR-D, there needs to be a continued development of the FCR requirements. This is assumed to be the first task of the next step of the project. This step will also include the work with establishing suitable supporting tools for the FCR providers. This in order to both ensure that current and harmonized tests are being performed, as well as lower the threshold for providers to be able to manage pre-qualification against the new requirements, that are seen as rather complicated requirements.

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