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Full Scale Frequency Response Tests in the Nordic Synchronized Area

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SUMMARY

Full scale tests have been performed by parallel feeding of 3 turbine governors in the Messaure hydro power station with a superimposed sinusoidal frequency signal with different period times and amplitudes. Sinusoidal power oscillations with amplitudes up to more than 70 MW have been created in the Nordic synchronized area. The period times of the sinusoidal oscillations have been 15, 25, 40, 60, 100, 150, and 250 s and the duration have been 20 cycles for each period time. As a result of the superimposed power oscillations, sinusoidal frequency oscillations have been created in the Nordic synchronized area with amplitudes up to 35 mHz. The analysis of the tests shows that it is possible to create rather large frequency oscillations by injecting comparatively small periodic power oscillations. The analysis also shows that there is a resonance peak in the frequency amplitude for period times around 60 s. This resonance peak was surprisingly higher during daytime tests as compared to night time tests. The shape of the amplitude and phase of the frequency oscillations agree fairly well with results found in related theoretical work. The agreement for period times shorter than a minute becomes better if also the load voltage dependence is included in the theoretical model of the Nordic synchronized area. The Nordic synchronous area dynamic power frequency characteristic increases with the applied period time; from about 500 MW/Hz at 25 s period time to about 3500 MW/Hz at 250 s period time. This behaviour is in line with results achieved when testing individual hydro units. The dynamic power frequency characteristic is significantly lower than the stationary power frequency characteristic that must never be less than 6000 MW/Hz in the Nordic synchronous area. The response from the HVDC connection to Estonia, Estlink 1, which is equipped with frequency control generally gives good damping of the injected power oscillations during the tests. For 60, 100 and 150 s period times Estlink 1 contributes with typically 60 % of the Finnish FCR-N response and about 15 % of the injected power amplitude in Messaure. During the tests some hydro units showed a bad response resulting in an amplification of the system frequency oscillations instead of reducing them.

KEYWORDS

Power systems, frequency variations, frequency oscillations, frequency control

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INTRODUCTION

Due to continuous degrading of the frequency quality in the Nordic power system for more than 15 years, ENTSO-E RGN decided in 2011 to start up several projects in order to find measures to improve the frequency quality. The project addressed in this paper is related to the observed frequency oscillations in the Nordic power system having a period time of typically 40-90 s and a magnitude of typically some tens of mHz, see example in Figure 1.

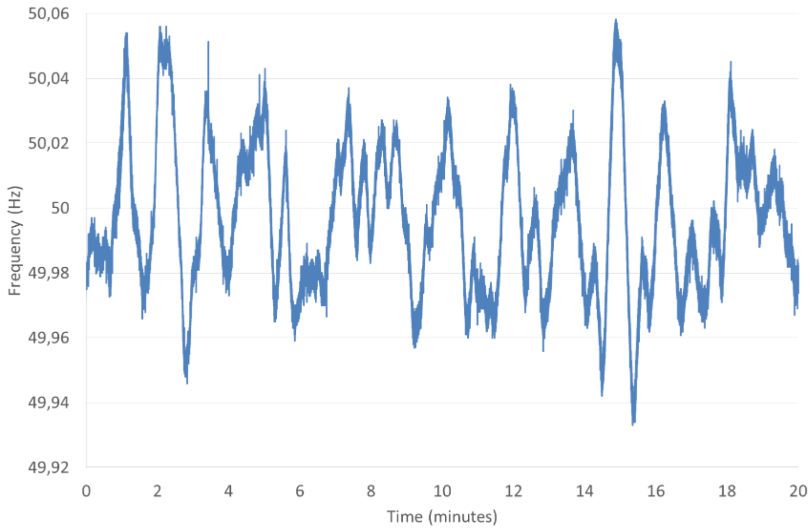

Figure 1 Frequency in the synchronized Nordic area May 29th 2015.

The frequency oscillations and the reasons behind these oscillations have already been studied [1]. Simplified models of the power system and the frequency controlling units have already been used in order to study the frequency oscillations in the power system [1, 2]. To verify individual units' frequency control, 12 tests have been performed on individual hydro units. However, 12 units is only a small part of the total number of units in the Nordic synchronous area used for frequency control. Therefore full scale tests have been performed in the Nordic synchronous area where sinusoidal power variations have been applied in order to study the system response. During these tests the overall behaviour of the power system can be studied including frequency control of generation units, system kinetic energy, load frequency dependence, etc. It will also give an answer to the project hypothesis, that rather small periodic power oscillations from load or generation, modelled as white noise, create the observed frequency oscillations in the power system.

THE TEST PROCEDURE

In the project two different possible ways of creating sinusoidal power oscillations of about 50 MW were identified.

- Using a large hydro power station
- Using an HVDC link connected to another not synchronized power system

Using an HVDC link for this test is from a technical point of view not a problem. However, from an administrative point of view it becomes more problematic, since it involves many countries connected to the other side of the HVDC link. Therefore it was decided to perform the tests by using the Messaure hydro power station, which is owned by Vattenfall and comprises three Francis turbines with a total rated power of 465 MW. Two test series were performed; one in October and one in March. The main purpose of the test in October was to check whether the test procedure was possible or not and the learnings from the test performed in October was then used for scheduling the test in March. During the tests two or three of the units were used in parallel. By feeding a superimposed sinusoidal frequency signal to the turbine governor of the units, a sinusoidal power variation was created and injected in the Nordic synchronous area. During the tests, the total added sinusoidal power amplitude from the three units was typically around 50 MW but during some tests it was more than 70 MW.

TEST FROM OCTOBER 30th 2013

During the tests performed on daytime 30th of October, two units were used in Messaure [3]. Tests were performed with a power oscillation period time of 40, 60 and 100 s. An example of the system frequency response is shown in Figure 2. As can be seen the responded system frequency becomes almost sinusoidal. The amplitude of the power oscillation varied from 33 to 72 MW as can be seen in Table 1. Each test had a duration of a few periods.

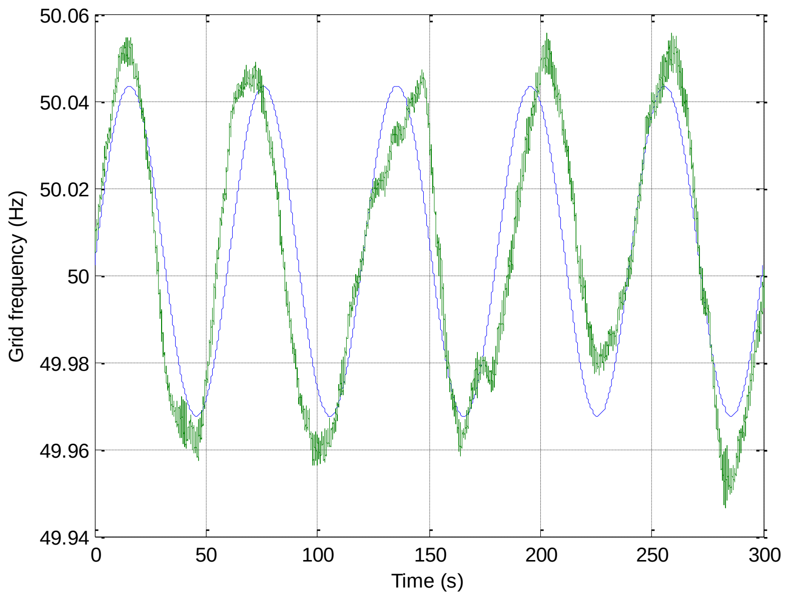

Figure 2 System frequency response, when applying a 53 MW sinusoidal power variation having a period time of 60 s, green curve shows the measured grid frequency signal and blue curve shows the estimated Fourier transform of the sinusoidal signal.

Table 1 Transfer function of injected power, $\Delta P_{Mes}(j\omega)$, to system frequency $\Delta f(j\omega)$, $H(j\omega)=\Delta f(j\omega)/\Delta P_{Mes}(j\omega)$, for different amplitudes and period times, T, of the injected power. Injected power reference, i.e. 0 degrees.

T [s]	$\Delta P_{Mes}(j\omega)$ [MW]	$\Delta f(j\omega)$ [Hz, degrees]		H(jω) [Hz/MW, degrees]	
40	33	0.018	∠ -32	0.000548	∠ -32
40	38	0.018	∠ -29	0.000490	∠ -29
60	22	0.008	∠ -53	0.000364	∠ -53
60	48	0.028	∠ 0	0.000579	∠ 0
60	56	0.035	∠ -14	0.000623	∠ -14
100	36	0.023	∠ 37	0.000648	∠ 37
100	46	0.022	∠ 35	0.000487	∠ 35
100	72	0.032	∠ 27	0.000464	∠ 27

In Figure 3 a Bode plot is shown from the linear analysis presented in [2]. The solid black line shows the behaviour of the linear model of the Nordic synchronous area when no frequency control is activated whereas the blue line shows the behaviour when having estimated frequency control in the system. “x” shows the results of the tests, see Table 1, where green “x” shows tests performed with the highest power amplitude at each period time. Green is therefore assumed to have the best accuracy as it is less affected by noise in the frequency signal.

As can be seen in Figure 3 the tests show that there is a resonance peak in the frequency oscillations. The peak arises when having a period time of around 60 s which is a longer period time as compared to the results achieved in the linear model [2]. As also can be seen in Figure 3, the gain for 40 s is lower as compared to the results achieved from the linear model. This is valid also when comparing with the linear model without frequency control.

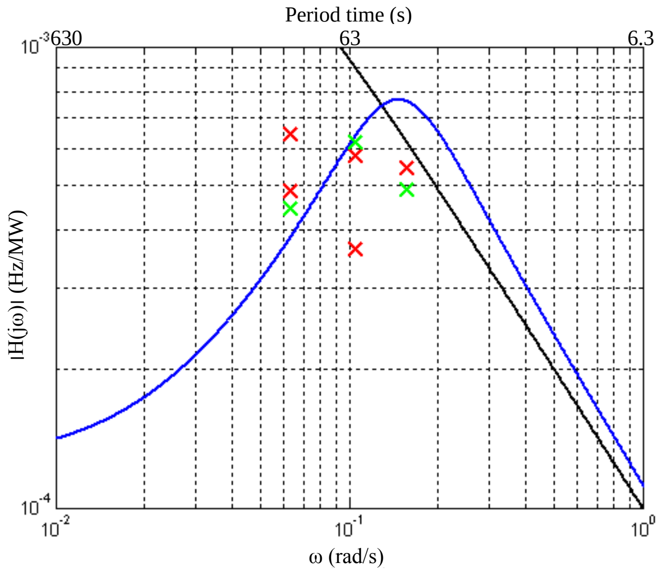

Figure 3 Bode plot of the gain (Hz/MW) from the linear analysis [1, 2] and tests performed [3, 4]. Solid black line is the linear model without frequency control, blue line is the linear model with frequency control, green "x" shows tests having the highest power amplitude and red "x" shows tests when having lower power amplitude.

FCR-N Response The applied power imbalance (in this case from Messaure), ΔP_{Mes}, will be taken care of by:

- The response of the generation units, $\Delta P_{FCR\text{-}N}$
- The load frequency dependence in the system, ΔP_f
- The change of kinetic energy of generation units and loads, ΔP_{kin}

The load frequency dependence is assumed to follow the frequency, i.e. when the frequency increases, the load in the system also increases. The change of kinetic energy in the system is due to a power imbalance between production and consumption in the system and results in a frequency derivative, i.e. the increase of system kinetic energy follows the frequency derivative. The superimposed frequency oscillation, Δf, in the system can be written as:

$$\Delta f = \Delta\hat{f} \times \sin(\omega \times t) = \Delta\hat{f} \times \sin\left(\frac{2 \times \pi}{T} \times t\right) \quad (1)$$

where T denotes the period time of the superimposed sinusoidal signal and $\Delta\hat{f}$ the amplitude of the frequency oscillation. The frequency derivative, $d\Delta f/dt$, can then be calculated as:

$$\frac{d\Delta f}{dt} = \frac{2\pi}{T} \times \Delta\hat{f} \times \cos\left(\frac{2 \times \pi}{T} \times t\right) \quad (2)$$

Based on the frequency derivative, the nominal frequency, f_0, and the system kinetic energy, W_{kin}, the power imbalance between generation and consumption can also be calculated:

$$\Delta P_{kin} = \frac{d\Delta f / dt}{f_0} \times 2 \times W_{kin} \quad (3)$$

During the analysis of the tests, the same values as in [2] have been used which means:

- The system kinetic energy is assumed to be 250 GWs
- The load frequency dependence is assumed to be 360 MW/Hz

Based on these assumptions and the measured frequency amplitude the power related to the load frequency dependence, ΔP_f, and the power related to the change of kinetic energy, ΔP_{kin}, have been calculated and summarized in Table 2.

Table 2 Summary of the different power response during the full scale test, only the highest amplitude for each period time is included, injected power, ΔP_{Mes}, reference.

T	$\Delta P_{Mes}(j\omega)$	$\Delta f(j\omega)$		$d\Delta f/dt\ (j\omega)$		$\Delta P_{kin}(j\omega)$		$\Delta P_f(j\omega)$		$\Delta P_{FCR-N}(j\omega)$	
[s]	[MW]	[Hz]	[degrees]	[Hz/s]	[degrees]	[MW]	[degrees]	[MW]	[degrees]	[MW]	[degrees]
40	38	0.018	∠ -29	0.0028	∠ 61	28	∠ -119	6	∠ 151	28	∠ 139
60	56	0.035	∠ -14	0.0037	∠ 76	37	∠ -104	13	∠ 166	47	∠ 138
100	72	0.032	∠ 27	0.0020	∠ 117	20	∠ -63	12	∠ -153	92	∠ 153

In order to get a power balance, the following equation is valid:

$$\Delta P_{Mes} + \Delta P_{FCR-N} - \Delta P_f = \Delta P_{kin} \qquad (4)$$

Based on the values given in Table 2 the power response from the units, ΔP_{FCR-N}, has also been included in the table. As can be seen the generation units' response, ΔP_{FCR-N}, vary both in phase and amplitude. Together with the load frequency dependence, ΔP_f, and the injected power in Messaure, ΔP_{Mes}, this gives an imbalance that must be taken care of by a change in the system kinetic energy, ΔP_{kin}. If the change of system kinetic energy is lower than the injected power, the generation units' response improves the situation, i.e. decrease the amplitude of the frequency oscillation. If, however, the change of system kinetic energy is higher than the injected power the generation units' response deteriorate the situation, i.e. increase the amplitude of the frequency oscillation. As can be seen in Table 2 the total generation response reduces the frequency oscillation for all tests performed.

TEST FROM MARCH 18th 2014

Test series were performed on 18th of March both during daytime and night time [4]. Tests were performed having a power oscillation period time of 15, 25, 40, 60, 100, 150 and 250 s. The amplitude of the power variation varied from 22 to 51 MW as can be seen in Table 3. Each period time was applied during 20 periods in order to achieve a good estimation of the measured signals.

Table 3 Transfer function of injected power to system frequency (power in, system frequency out), $H(j\omega)=\Delta f(j\omega)/\Delta P_{Mes}(j\omega)$, for different period times of ΔP_{Mes}, injected power, ΔP_{Mes}, reference.

Time of test	T [s]	$\Delta P_{Mes}(j\omega)$ [MW]	$\Delta f(j\omega)$ [Hz, degrees]		$H(j\omega)$ [Hz/MW, degrees]	
00:16:42-00:34:42	60	38	0.022	∠ -6	0.000574	∠ -6
00:40:52-00:52:12	40	36	0.020	∠ -45	0.000554	∠ -45
01:06:12-01:43:42	150	36	0.017	∠ 36	0.000475	∠ 36
01:54:17-03:09:17	250	34	0.010	∠ 28	0.000286	∠ 28
03:15:33-03:43:53	100	40	0.022	∠ 32	0.000551	∠ 32
03:47:43-03:54:23	25	36	0.010	∠ -68	0.000280	∠ -68
03:59:58-04:03:43	15	20	0.004	∠ 144	0.000177	∠ 144
10:04:39-10:21:39	60	49	0.040	∠ -8	0.000808	∠ -8
10:29:39-10:40:59	40	42	0.026	∠ -45	0.000626	∠ -45
10:56:54-11:34:24	150	38	0.014	∠ 23	0.000363	∠ 23
12:01:42-13:16:42	250	38	0.011	∠ 44	0.000285	∠ 44
13:23:32-13:46:52	100	44	0.022	∠ 54	0.000512	∠ 54
13:49:44-13:54:19	25	40	0.014	∠ -74	0.000341	∠ -74
13:58:31-14:00:01	15	22	0.002	∠ 118	0.000088	∠ 118

In Figure 4 and Figure 5 Bode plots are shown from the linear analysis presented in [2]. The solid black lines show the behaviour of the linear model when no frequency control is activated, whereas the blue lines show the behaviour when having estimated frequency control. The "x" show the results of the tests performed, see Table 3, where blue "x" show the tests performed during night time, green "x" tests performed during daytime and red "x" show tests performed 30th of October.
The shape of both the amplitude and the phase shift seem to follow the theoretical models from the linear analysis presented in [2]. However, it is important to consider that the measured data are

equipped with uncertainties, since the amplitude of the injected power oscillation in Messaure was limited to 40-50 MW (about 20 MW for the 15 s period time), and therefore resulted in a limited amplitude of the frequency oscillations of some tens of mHz. As the response in frequency was less for short and long period times, it is likely that the uncertainties are highest for short (15 s) and for long (250 s) period times.

If studying the amplitude in more detail, it can be seen that the peak is more pronounced during the daytime tests as compared to night time tests and that the peak arises around a period time of 60 s. This can be compared with the linear analysis [2] that gives the peak around 45 s. The peak is also higher during daytime tests as compared to night time tests.

As the generation and consumption in the system are higher during the daytime tests, i.e. more kinetic energy in the system, probably more FCR-N from Norway, and probably higher droop settings on the units in Sweden, the opposite behaviour had been expected. However, for some units having a considerable backlash a higher droop setting can work in the other direction and giving higher oscillations. This was found during tests on individual units [3].

For the 40 s, 25 s and 15 s period time, it can also be seen that the amplitude is higher during daytime tests as compared to night time tests and that the test results are lower as compared to the results achieved from the linear model. The gain is also lower if comparing with a system without frequency control (black solid line). In a system without frequency control it is only the load frequency dependence and the system kinetic energy that limits the resulting gain.

As the simplified linear model does not include the load voltage dependence simulations have also been performed in a full scale dynamic PSS/E model of the Nordic synchronized area. In the PSS/E simulations both load voltage and load frequency dependence have been included whereas the turbine governor impact has been excluded. In the PSS/E simulations the load flow of the system has been adopted to the situation valid during the tests. Sinusoidal power injections have then been simulated from the same power station (Messaure) as during the real tests. The period time and the power amplitude have been adjusted to the same values as during the real tests. The simulation results (15 s, 25 s and 40 s period times) are marked as black “o” in Figure 4 and Figure 5. As can be seen in the diagrams the agreement with the test results becomes better, if also implementing the load voltage dependence in the simulation model.

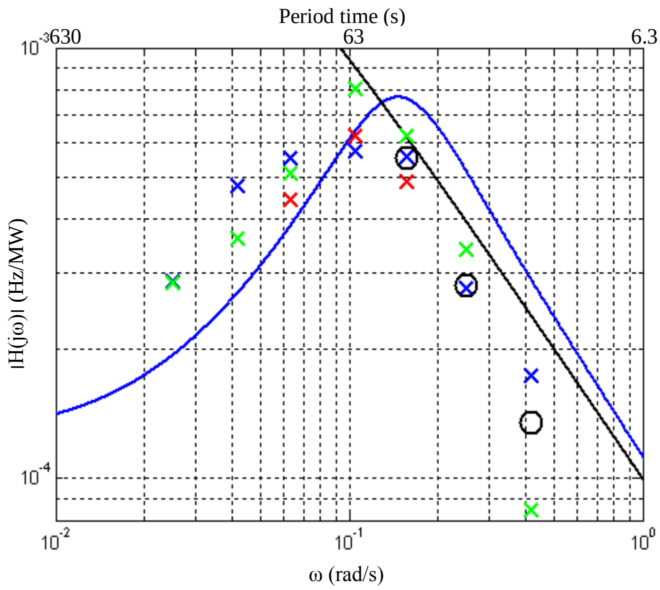

Figure 4 Bode plot of the gain (Hz/MW) from the linear analysis [2] and tests performed [3, 4]. Solid black line is the linear model without frequency control, blue line is the linear model with frequency control, black “o” is the full scale PSS/E model with load voltage and load frequency dependence but without frequency control, blue “x” show the nighttime tests, green “x” show the daytime tests, and for comparison also the tests performed 30th October are included with red “x”.

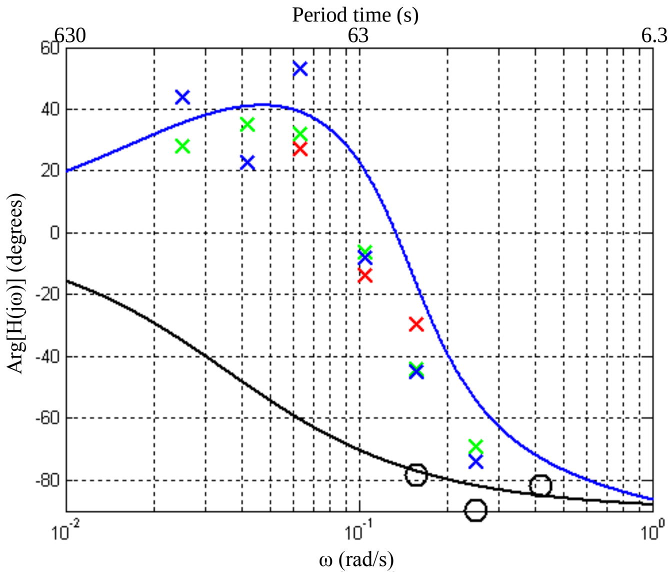

Figure 5 Bode plot of the phase (degrees) from the linear analysis [2] and tests performed [3, 4]. Solid black line is the linear model without frequency control, blue line is the linear model with frequency control, black "o" is the full scale PSS/E model with load voltage and load frequency dependence but without frequency control, blue "x" show the night time tests, green "x" show the day time tests and for comparison also the tests performed 30th October are included with red "x".

For longer period times the amplitude of the test results in Figure 4 is higher as compared to the results from the linear model. This indicates that the dynamic power frequency characteristic in the system is lower than expected. Explanations to this can be uncertainties in the estimated frequency amplitude, other parameter settings of turbine governors, the use of filters and floating dead bands in many Finnish hydro units, together with mechanical backlash in the servos of the hydro units that have been observed during tests on individual units.

During the test measurements were also made in a number of hydro power stations and on some HVDC links. Most of the units contributing with frequency control had a good and expected behaviour. For some units, however, the behaviour was very bad. Figure 6 shows one of the worst examples. In the figure it can be seen that the power response from a unit participating with frequency control, red curve, is perfectly in phase with the injected power disturbance from Messaure, blue curve. This means that the system power imbalance and thereby the grid frequency deviation will be higher as compared to if the unit would not have participated with frequency control.

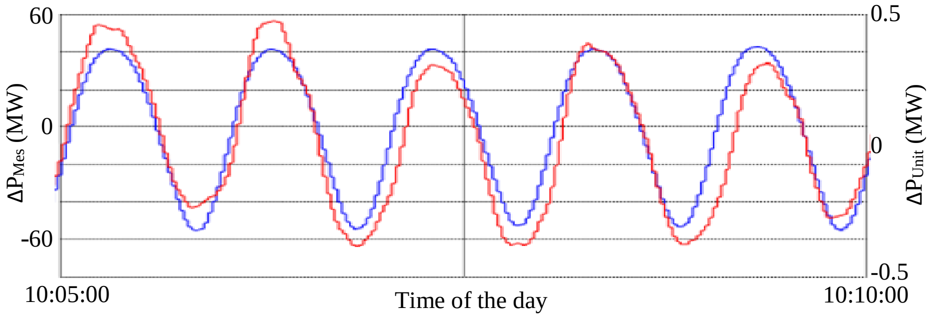

Figure 6 Power injected in Messaure, blue, and responded power from a hydro unit, red.

During the tests the power transfer on the Finnish HVDC links Estlink 1 and the Vyborg (Russian HVDC connection) were measured by PMUs. In Figure 7 the Estlink response for one of the 60 s period time tests is shown. As can be seen the response becomes rather sinusoidal and the phase shift between injected power in Messaure and the Estlink response is calculated to 123 degrees. For 60, 100 and 150 s period times Estlink 1 contributes with typically 60 % of the Finnish FCR-N response and about 15 % of the injected power in Messaure. In the same way as for hydro turbines contributing with FCR-N the power frequency characteristic increases with increased period time of the oscillation.

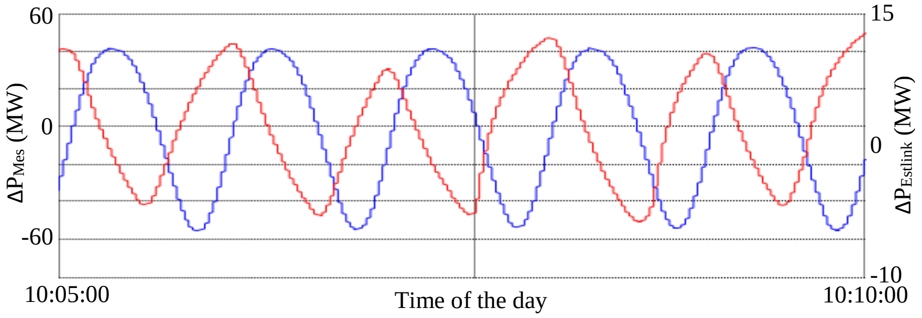

Figure 7 Power injected in Messaure, blue, and responded power from Estlink HVDC, red.

FCR-N Response As previously described the network power frequency characteristic will depend on

- the generation units response, $\Delta P_{FCR\text{-}N}$
- the load frequency dependence, ΔP_f
- the change of kinetic energy in the system, ΔP_{kin}

During the tests the kinetic energy was estimated based on the generation level of different generation sources in the system, assumed system loading as well as loading, power factor and inertia constant of the different generation sources. The total kinetic energy in the system is presented in Table 4.
The load frequency dependence has been assumed to be 360 MW/Hz during all the tests which is in accordance with the assumption during the test 30th October and with the linear analysis presented in [2]. This is a simplification as the load frequency dependence probably will vary between night and day and due to the system loading. However, there are uncertainties in the estimation of the load frequency dependence, and the related power reduction is significantly less as compared to the other power changes.
Based on the injected power in Messaure, the derived frequency oscillation (see Table 3), the derived frequency derivative, the calculated system kinetic energy, the assumed load frequency dependence and the estimated kinetic power are summarized in Table 4, as well as, the change of load due to the load frequency dependence and the estimated response from the system FCR-N.
As can be seen a large part of the system response is related to the change of the system kinetic energy. Generally the impact from this change of kinetic energy is higher for shorter period times.

Table 4 Results for the Nordic system. Estimated kinetic energy, W_{kin}, power injected in Messaure, ΔP_{Mes}, estimated kinetic power, ΔP_{kin}, estimated power caused by load frequency dependence, ΔP_f, and estimated change of generation ($\Delta P_{FCR\text{-}N}=\Delta P_{Mes}-\Delta P_{kin}-\Delta P_f$), reference is injected power in Messaure.

Time of test	T [s]	W_{kin} [MWs]	$\Delta P_{Mes}(j\omega)$ [MW]	$\Delta P_{kin}(j\omega)$ [MW, degrees]	$\Delta P_f(j\omega)$ [MW, degrees]	$\Delta P_{FCR\text{-}N}(j\omega)$ [MW, degrees]
00:16:42-00:34:42	60	206794	38	19 ∠ 84	8 ∠ -6	33 ∠ 148
00:40:52-00:52:12	40	207063	36	26 ∠ 45	7 ∠ -45	18 ∠ 133
01:06:12-01:43:42	150	205456	36	6 ∠ 126	6 ∠ 36	35 ∠ 166
01:54:17-03:09:17	250	205747	34	2 ∠ 118	4 ∠ 28	32 ∠ 174
03:15:33-03:43:53	100	2111211	40	12 ∠ 122	8 ∠ 32	42 ∠ 160
03:47:43-03:54:23	25	212341	36	22 ∠ 22	4 ∠ -68	15 ∠ 163
03:59:58-04:03:43	15	214015	20	13 ∠ -126	1 ∠ 144	48 ∠ -168
10:04:39-10:21:39	60	250478	49	42 ∠ 82	14 ∠ -8	49 ∠ 127
10:29:39-10:40:59	40	249338	42	41 ∠ 45	9 ∠ -45	23 ∠ 105
10:56:54-11:34:24	150	247151	38	6 ∠ 113	5 ∠ 23	36 ∠ 169
12:01:42-13:16:42	250	246459	38	3 ∠ 134	4 ∠ 44	37 ∠ 173
13:23:32-13:46:52	100	246453	44	14 ∠ 144	8 ∠ 54	52 ∠ 164
13:49:44-13:54:19	25	246190	40	33 ∠ 16	5 ∠ -74	8 ∠ 144
13:58:31-14:00:01	15	245959	22	8 ∠ -52	1 ∠ 118	29 ∠ -174

Another way of presenting the FCR-N response is to calculate the dynamic power frequency characteristic in the system, i.e. divide the estimated system FCR-N contribution with the frequency response in the power system. Then, it is possible to compare the power frequency characteristic achieved for each period time with the system total power frequency characteristic (from FCR-N) that is specified to never be less than 6000 MW/Hz in the synchronized Nordic system.
Except comparing with the stationary power frequency characteristic, it is also possible to compare the results with tests performed on individual units where superimposed sinusoidal frequency signals with different period times have been applied on the turbine governors in the same way as described above. In Figure 8 the dynamic power frequency characteristic is shown for the derived system FCR-N. In the figure it can be seen that the dynamic power frequency characteristic is roughly 500 MW/Hz at a period time of 25s and increases to around 3500 MW/Hz at 250 s period time.

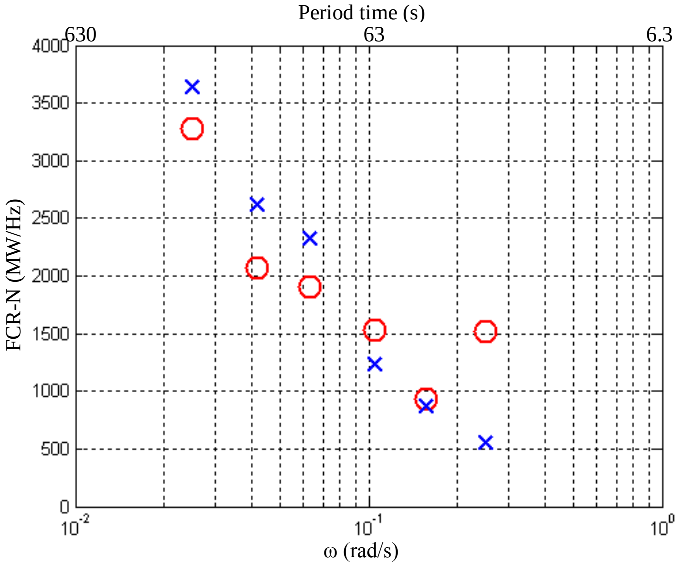

Figure 8 Total (estimated FCR-N) dynamic power frequency characteristic in the system, blue "x" indicates nighttime tests and red "o" daytime tests.

CONCLUSIONS

Based on the full scale tests performed in Messaure 30th October 2013 and 18th March 2014 it is concluded that:

- An estimate of the behaviour of the frequency control in the Nordic synchronous area is possible to derive by injecting a power oscillation into the system.
- Rather small periodic power oscillations will create rather big periodic frequency oscillations. The applied power oscillations resulted in frequency oscillations with an amplitude up to 35 mHz.
- There is a resonance peak in the frequency amplitude for period times around 60 s. During the tests this resonance peak was surprisingly higher during daytime as compared to night time tests.
- The amplitude of the frequency oscillations agrees fairly well with results found in previously performed theoretical work. The phase shift between applied power and the grid frequency varies with period time and the results agree fairly well with previously performed theoretical work. If the load voltage dependence also is included in the simulation model the agreement with the tests results becomes better.
- The measured dynamic power frequency characteristic from FCR-N in the system at period times longer than 100 s is lower than the one derived in the theoretical analysis. Explanations to this can be less system dynamic power frequency characteristic, other parameter settings of the governors, the use of filters and floating dead band on Finnish units and mechanical backlash in the servos on hydro units.

- The system FCR-N have been estimated and it can be seen that the Nordic synchronous area dynamic power frequency characteristic increases with the applied period time; from about 500 MW/Hz at 25 s period time to about 3500 MW/Hz at 250 s period time. This behaviour is expected and corresponds well with the behaviour achieved when testing individual hydro units. The dynamic power frequency characteristic is, however, significantly lower than the stationary power frequency characteristic that never shall be less than 6000 MW/Hz.
- The response from the Finnish HVDC (Estlink 1 and Vyborg HVDC), especially Estlink 1, give good damping of the injected power oscillations. For 60, 100 and 150 s period times Estlink 1 contributes with typically 60 % of the Finnish response and about 15 % of the injected power amplitude in Messaure.
- Measurements performed on individual hydro units show that most units have expected behavior. However, some units have responses that amplifies the injected power oscillation, i.e. an unwanted behavior seen from the system point of view.

When drawing conclusions of the tests performed it is very important to consider that measured data as well as estimated system parameters are associated with uncertainties. This can clearly be seen for some of the tests and analyses where individual results seem to be outliers. The biggest uncertainty is probably from the 15 s period time tests where the injected power amplitude was limited to only 20 MW.

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