



Norwegian University of  
Science and Technology

# Balancing of Offshore Wind Power in Mid-Norway

Implementation of a load frequency control scheme for handling  
secondary control challenges caused by wind power

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# Problem Description

Norway suffers from an energy deficit in years with average and poor precipitation. The power generation capacity in Norway should thus be expanded in order to secure an independent and stable electric power and energy supply. Since commissioning of new large hydro or thermal power plants aren't considered as options, large offshore wind farms may be among the electric power supply technologies to form the Norwegian electric power system in the future. Large offshore wind farms seem like a promising alternative due to a favourable wind regime along the vast Norwegian coastline, but some technical tasks require in-deep investigations before the construction of such wind farms can take place. So far, grid integration of 350 MW including the power balancing and frequency control of offshore wind power has been accepted in Norway.

The main objective of this thesis is to investigate the task of maintaining power balance and prevention of frequency excursions in the Norwegian power system in conduction to grid-connection of a 1000 MW offshore wind farm. Such frequency excursions may be caused by fast power output fluctuations from a large offshore wind farm: Operational experience from the 160 MW Danish offshore North Sea wind farm Horns Rev 1 has shown that the power output is, in periods, subject to rapid, excessive, hours-lasting, repeating-character fluctuations with wind and power gradients so excessive that the power output changes between zero and rated within a less than 15 minutes period. Using this Danish experience as a reference, the impact of power output fluctuations on the Norwegian power system will be investigated, targeting improvement of the power system balance and reduction of frequency excursions. Possible control suggestions will be given, for instance utilizing a load frequency controller.

In this thesis, a 350 MW and a 1000 MW offshore wind farm will be connected to the county Møre and Romsdal in western Norway as the area suffers from both poor generation capacity and grid transmission constraints. A model of the Norwegian power system will be used to find out:

- 1        How the area's hydro power plants are to be used to:
  - A:        Prevent excessive frequency deviations due to the wind farm
  - B:        Maintain the power balance in the Norwegian power system by implementing so-called Load Frequency Control
- 2        How the wind farm will influence on the some short-term stability of the onshore power system

The simulation program DlgSILENT PowerFactory is chosen as the main project tool.

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Supervisor: Terje Gjengedal, ELKRAFT



## Preface

This master thesis has been written at the Department of Electrical Engineering at the Technical University of Denmark during the spring of 2009 in cooperation with the Norwegian power company Statkraft. The thesis is a continuation of a premaster project that I wrote at the same place during the autumn of 2008. The premaster project also dealt with power balance challenges (Gleditsch, 2008).

A few comments on the report:

- From 1.7.2009 the new European Network of Transmission System Operators for Electricity (ENTSO-E) took over for the existing TSO associations in Europe, among others Nordel and UCTE. The old organization names have mainly been used in references to papers and reports that have not yet been replaced by ENTSO-E, so the old names and abbreviations have been used.
- The references have been included in the text with author names and publishing date, instead of numbers. This is due to personal preference. Page numbers of references are only included in the text and only when relevant.
- If all simulation graphics (several scores) were included, the thesis would have exceeded the thickness of a book. As an attempt to reduce the size of the report, results that are judged not to contribute to increased understanding of the objectives of the thesis aren't included – not even in the appendixes. They can be acquired from the author upon enquiry.
- During the last read-through it was discovered an incongruity between the FRT requirements and simulations. As stated in subchapter 5.4, generation units in Norway shall withstand a 150 ms lasting voltage drop to 0 in the network to which the unit is connected, prevailing for networks with voltages over 200 kV. Unfortunately all FRT simulations were run with a 100 ms lasting voltage drop of such. It is assumed that running the simulations with the correct fault length would bring the same results.

To briefly sum up the last year from a personal benefit point of view; it has been very interesting to get a novice insight into wind power and to study the interplay between hydro and wind power. To visit a foreign university has also been an experience I wouldn't miss out on.

I would like to thank Vattenfall for providing real time wind data, Sintef for providing the grid model, and my supervisors Terje Gjengedal at NTNU and Arne Hejde Nielsen at DTU for their support. Special thanks go to my head supervisor Vladislav Akhmatov at DTU for his clever advises and suggestions and his valuable and time-consuming help with modelling and simulating.

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## Abstract

In order to comply with governmentally announced greenhouse gas emission reductions goals and to consolidate an independent and stable electric power and energy supply, Norway must increase its installed renewable energy based power generation capacity. Profitability estimations, today's available technical solutions and regulations concerning preservation of natural resources leave construction of new small hydro power plants behind as the most plausible alternative together with construction of wind farms. Global trends such as technologic development and progress and the public opinion indicate that future wind farms in Norway will be located offshore. The assumption is supported by the recent handing out of a concession to an offshore wind farm project for the first time in Norwegian history. The projects name is Havsul 1 and the licence involves construction of 350 MW offshore wind power. Havsul 1 will be located in Mid-Norway, which is the region in Norway where the Norwegian Transmission System Operator (TSO) Statnett is most concerned about their ability to execute their task of assuring safety of power supply in the future. The concern owes to lack of generation capacity and transmission constraints.

Experience show that commissioning of large offshore wind farms will impose power balance associated challenges on the TSO. By applying a slightly modified model developed by Sintef of the Nordel synchronous system in the power simulation tool DIgSILENT PowerFactory, grid connection of 350 MW and 1000 MW offshore wind farms to a bus bar representing Mid-Norway were investigated, targeting reduction of frequency excursions. To execute the reduction task, a so-called centralised Load Frequency Control (LFC) scheme was implemented and four hydro power plants were designated to provide regulating power pursuant to a priority key that used their response times as input. To simulate power fluctuations in the time span of hours, real time wind data acquired from the Danish offshore wind farm Horns Rev 1 was used as input in the offshore wind farm model. These data were kindly provided by the Swedish power company Vattenfall.

The power fluctuations simulations showed that LFC is a well-fitted tool for bridling frequency excursions in the Nordel synchronous system caused by fluctuating power generation in an offshore wind farm. During the power fluctuations, which were of a particularly challenging kind, the system frequency complied with Statnett's normal operation requirements of  $50 \pm 0.1$  Hz. The results weren't too surprising since LFC has been used successfully in Europe for many years. They did however show that the amounts of the so-called frequency controlled normal operation reserves in Nordel may need to be expanded in case of a massive expansion in wind power in Norway.

Fault Ride Through (FRT) investigations were also conducted by introducing 3-phase short circuit faults at selected bus bars. The simulations showed that the FRT requirements in Norway were not violated even in the worst case simulations.

Some choices regarding the setup of the model may have exalted the simulation results.





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## Nomenclature

Abbreviations are also transcribed at first appearance in the document.

ACE	-	Area Control Error
AGC	-	Automatic Generation Control
DFIG	-	Doubly Fed Induction Generator
FCDR	-	Frequency Controlled Disturbance Reserve
FCNOR	-	Frequency Controlled Normal Operation Reserve
ENTSO-E	-	European Network of Transmission System Operators - Electricity
HVAC	-	High Voltage Alternating Current
HVDC	-	High Voltage Direct Current
LFC	-	Load Frequency Control
NGC	-	Nordic Grid Code
NSA	-	Nordic Synchronous Area
NTNU	-	Norwegian University of Science and Technology
NVE	-	Norwegian Water Resource and Energy Directorate
PU	-	Per Unit
TSO	-	Transmission System Operator
UCTE	-	Union for the Co-ordination of Transmission of Electricity
WTG	-	Wind Turbine Generator



## 1 Introduction

The energy consumption in Norway is increasing year by year, resulting in an energy deficit in years with average and poor precipitation. The power supply situation is especially stressed in Mid-Norway. One third of the energy needed in the area over a year must be imported under the presumption of average consumption and precipitation, and the import transmission capacity is approaching its upper boundary. The power generation capacity should thus be expanded in Norway in general and in Mid-Norway in particular in order to secure an independent and stable electric power and energy supply in the future.

Since commissioning of new, large hydro or thermal power plants aren't considered as options due to environmentally focused political resolutions, the energy deficit must be covered by new renewable power generation. Large onshore and offshore wind farms may be among the electric power supply technologies to form the Norwegian electric power system in the future, because other forms of renewable power generation aren't seen to be financially and technically competitive in the nearest future. Large offshore wind farms seem like a specially promising alternative due to a favourable wind regime along the coastline, but some technical tasks require in-deep investigations before the construction of such wind farms should take place.

This thesis will focus on one of these technical issues; Grid integration of an offshore wind farm into the Norwegian hydro power based electrical power system. Special attention will be devoted to the task of mitigating system frequency excursions from the desired level by implementing a so-called Load Frequency Control (LFC) scheme and utilizing specially assigned hydro power plants to provide reserve power. At the end of the 90s, before commissioning of the HVDC cables to the Netherlands and to Germany, it was suggested that the Nordel synchronous system model of partly manually controlled secondary power reserves might be inadequate (Bakken, et al., 1998). The problem may arise again in the case of a significant expansion in commissioned wind power, and so this thesis has investigated whether implementation of a basic LFC scheme may be a satisfactory solution to the load frequency control problem. Among the different LFC schemes, the so-called centralized one was chosen because it's easy to implement and plain to comprehend.

Some fault ride through and forced shut-down simulations were also conducted since these phenomena are likely to occur from time to time during life-long operation of a wind farm. They may thus strengthen the impression of how a large offshore wind farm would affect the Nordel synchronous system.

The report is structured as follows: Chapter 2, 3 and 4 presents background information; chapter 2 on hydro and wind power in Norway, chapter 3 on the basal characteristics of hydro and wind power generation and chapter 4 on Mid-Norway as the area in Norway with the greatest energy and power balance and quality challenges. Chapter 5 then presents the theory behind LFC which as a mean for curbing power balance and quality challenges. Chapter 6 merges the hydro and wind power interplay in Norway and the LFC theory by presenting a model of the Nordel synchronous system in which the LFC has been implemented. The remaining chapters round it all off by presenting short and long term simulations on the model from chapter 6 and discussing the impact an offshore wind farm would have on the Norwegian power system.

## 2 Hydro and wind power in Norway

This chapter introduces hydro and wind power as players on the Norwegian electricity market.

### 2.1 Hydro power in Norway

Norway is from a power production point of view not only blessed with much precipitation, but also with distinct seasonal-changing climate and extensive mountain scenery. Roughly speaking, the precipitation falls as snow in the wintertime, and during spring and summer the snow melts and flows into the high-levelled natural lakes that the mountains hold. The precipitation level and the mountain lakes' storage capacities are so great that Norway's annual energy demand can be met more or less entirely by power generation in hydro power plants.

Norway's hydro power resources may be comparable to the oil resources when it comes to importance for the national economy and development as an industrial nation during the past century, but by now, most major water systems are either protected or already utilised. This leaves upgrading of existing plants and construction of less-than-10 MW plants behind as development and expansion possibilities for the national hydro power industry in the future. This subchapter will account for hydro power's influence on the evolution of modern Norway so far and bring some reflections on hydro power's likely future development in Norway.

#### 2.1.1 Historical retrospect

The fresh water resources were first taken use of in electricity production for illumination of a nickel works at the island Senja in 1882. Thereafter, some hydro power plants were constructed here and there during the 1890s, mainly for lightning up streets, public buildings, industry etc. As with electrical engineering, hydro power technology evolved rapidly during the end of the 19<sup>th</sup> century, and at the beginning of the 20<sup>th</sup> century industrial establishments sprung up around the most easily accessible water resources. A period of strong economic expansion followed the turn of the century and Norway saw a large expansion in hydro power plants. The importance of the resource turned out clearer and clearer, and so the law of reversionary right was proposed. The intention of the law was to keep the natural resources in the hands of the people of Norway; it declares that the production license to a waterfall will be reset to the Norwegian state 60 years after a concession has been given to a power production company. The law was carried out in 1917 (Directorate for Cultural Heritage, 2005).

After a construction decline in the period of the great depression, the armament industry's needs helped the construction rate of new hydro power plants to increase once more, and after the Second World War, the hydro power expansion continued massively through the 60s, 70s and 80s, powering the working class' homes. Few large hydro power plants were constructed throughout the last part of the 80s and the 90s, and in 2001 the Norwegian Prime Minister announced in his New Year's speech that the era of great hydro power constructions was past (Stoltenberg, 2001). His statement wasn't addressed to lack of potential, but alluding to the fact that most major water systems were either utilised already or protected, i.e. actions have been taken to prevent destruction and depreciation of the remaining natural values. After the speech,



some large projects experienced closing or reductions in concession rights, emphasizing and substantiating the governmental environmental priorities. As examples, Statkraft's 1.5 TWh/year Vefsna-project was abandoned (Statkraft, 2005) and the Øvre Otta-construction and the Sauda-construction were both halved from approximately 1 TWh/year to 500 GWh/year (Fornbar.no, 2009) after recommendations from the Norwegian Water Resource and Energy Directorate (NVE). NVE is responsible for the administration of Norway's water and energy resources and one of its tasks is thus to consider power plant concessions.

### **2.1.2 Potential and future outlooks**

Norway's total theoretical hydro power resource base is estimated to comprise around 600 TWh/year, but a 2005 study estimated that only construction of 205 TWh/year of the above number could be justified from an economical and technical point of view. Moreover, 44.2 TWh/year of the 205 TWh/year feasible potential are in protected zones and hence not available as potential hydro power resources. Today's hydro power plants are estimated to produce 121.8 TWh/year in a mean precipitation year, calculated on the basis of the precipitation in the period 1970-1999, leaving behind an unprotected potential of 37.7 TWh/year.

Roughly one third of the unprotected potential is attributed to upgrading and expansion of large existing plants, and the rest to construction of small hydro power plants. The notions small and large refer to hydro power plants smaller and larger than 10 MW in this context. In 2007 the government drew up a set of instructions regarding small hydro power plants that are to be used by regional authorities and NVE in concession processes and development plans. The instructions include recommendations that will ease the licensing process for small hydro power plant projectors, and it was produced to stimulate land owners to contribute to realisation of the potential. NVE has estimated that roughly 5.5 TWh/year of the small hydro power plant potential is located in Mid-Norway, which is the area of focus in this thesis (ref. chapter 4).

Norway is Europe's largest hydro power producer and with over 100 years of experience, the Norwegian hydro power industry has built up expertise in all aspects of hydro power plant constructions, from planning and construction to delivery of technical equipment. Due to the limited national possibilities for new constructions, the industry has shifted its focus more towards foreign projects, demonstrated in e.g. SN Power's (Norwegian based international hydro power company) extensive Latin American and Asian activities and Statkraft's increasing south-eastern Europe priority.

All numbers in this subchapter have been taken from (Ministry of Petroleum and Energy, 2008, pp. 19-30). The paper is an annual governmental fact sheet on Norway's energy and water resources.

## **2.2 Wind power in Norway**

While hydro power's effect on the development of Norway cannot be underestimated, wind power is still a novice on the Norwegian electricity market. The electricity generation distribution illustrates this: In 2007, hydro power plants accounted for 98.3% of Norway's total electricity generation and wind turbines for 0.7% (NVE, 2009). This picture might change during the next decades; Norway needs to build up their power generation capacity and the government has set

quite ambitious climate goals that will be described more thoroughly in subchapter 2.2.3. This implies that the new power generation shall be mainly by renewable energy resources, which, as explained in subchapter 2.1.2, most likely involves limited construction of hydro power plants. This paves the way for wind power, owing to the fact that Norway has some of Europe's finest wind resources. The great hydro power resources and a restrictive environmental policy have restrained large wind farm constructions and the national wind industry so far, but CO<sub>2</sub> emission reductions goal may be the pushes necessarily needed to evolve as a wind power nation. A governmentally ordered report supports this, as it concludes that the combination of two mutually beneficial Norwegian circumstances, i.e. great offshore wind resources and long-lasting acquired offshore technology experience, brings promises that a major industry can be built up around offshore wind power - if only Norway makes this a priority area as soon as possible (Norwegian Energy Council, 2008).

This subchapter is an introduction to wind power's short history in Norway and include presentation of potential for future constructions and considerations on what construction rate to expect in the future. Special attention will be devoted to Mid-Norway area in this thesis (for reasons accounted for in chapter 4) so this chapter rounds of with a look on wind power in Mid-Norway.

A key source to this subchapter was (IEA Wind, 2008, pp. 203-208).

### **2.2.1 Historical retrospect**

Although Norway's first electricity producing wind turbine was installed already in 1916 (Lereim, 2006), wind power hasn't played a role in the industrialisation of the country. During the 20<sup>th</sup> century Norway seemed to have inexhaustible hydro power resources, and since hydro power technology was low-priced and well developed, wind energy was never considered as an alternative to hydro power.

The picture started changing at the end of the 20<sup>th</sup> century as most major hydro power resources were exploited or protected. As subchapter 2.1.1, reports the low hydro power development rate culminated in a Prime Minister speech of which the message paved the way for other energy resources. Since the 2001 speech, six wind farms with installed capacity of 40 MW or more have been constructed onshore in Norway, with Smøla 2 from 2005 being the biggest with 110 MW. Norway is nevertheless widely labelled underdeveloped as a wind power nation since some of Europe's greatest wind resources are found along the coastline. The total installed wind power capacity in Norway is 428 MW by the end of 2008 (EWEA, 2009) and no offshore wind turbines are constructed to this date.

### **2.2.2 National potential**

In 2007, a governmental enterprise estimated Norway's offshore wind power potential to 14 000 TWh/year (Enova, 2007), i.e. approximately 100 times Norway's average yearly consumption. The major parts of the potential were identified on depths that require floating wind turbines for power generation, or in other words technology that isn't commercially available today. A substantial potential was however identified in low-depth areas: 800 TWh/year of constructionable wind power was detected in areas with depths less than 50 meters and approximately 180 TWh/year in areas with depths less than 10 meters (NVE, 2003). The

technology for construction of wind turbines founded on the seabed on such depths is well known, but the report emphasized that wind power constructions in the low-depth coastal areas would in general be controversial due to visual pollution, vulnerable maritime wildlife etc. It shall also be noticed that even if the low-depth area resources are available in the sense that they are physically constructionable, there report holds no restrictions on the figures with respect to pecuniary, environmental or safety interests. This means that only a fraction of the resources will in fact potentially be of interest for constructions.

Common for all possible Norwegian offshore wind farm constructions is that merely a marginal development of the total potential will imply heavy power export. The 60 meter depth areas to the east of the Southern Oil Fields should thus be appealing, since power from these areas can be exported to Denmark, Germany, Great Britain and the Netherlands and since seabed-founded wind turbines can be constructed on such depths (Blue H, 2009).

Half of Norway's offshore wind resources are in the three northernmost counties (NVE, 2003). The resources in Mid-Norway will be deepened in chapter 2.2.4.

### **2.2.3 Future outlooks for national wind power development**

In a 1999 white paper the Norwegian government announced a goal of 3 TWh/year of electricity generated in wind turbines within 2010 (Ministry of Petroleum and Energy, 1999). Owing to the good coastal wind regime the goal can be reached by construction of more or less 1000 MW of offshore wind power (Sintef, 2009). Chapter 2.2.1 reports that less than half of this is installed by now, and since 2010 is half a year away as this is written there is no indication that the goal will be reached. In a white paper of 2007, a new goal was added to the climate policy; new renewable energy production and energy efficiency improvement shall comprise 30 TWh/year within 2016 (Ministry of the Environment, 2006-2007) referenced to the 2001 level. To what extent wind power shall contribute to the goal wasn't clearly expressed, but a massive expansion in installed wind power generation capacity will indisputably be needed to reach the target.

Wind power isn't economically justifiable with the current energy prices in Norway which are relatively low, and a governmental support scheme is therefore needed if more wind farms shall be constructed in the future. This is making wind power highly controversial; extra costs will eventually be put upon the consumers, breathing life into the arguments of the wind power opponents; hydro power production costs are close to zero, Norwegian gas power plants are more environmentally sound than European coal fired power plants etc. At the same time, NVE's concession department has limited capacity, delaying construction concession decisions and appeals. Still, for the first time, a Norwegian offshore wind power project has been licensed by NVE, i.e. the 350 MW Møre og Romsdal project Havsul 1. The project is deepened in chapter 2.2.4.3.

The poor support schemes and tardy executive works have influenced the working force resource management in some of the big wind power players in the Norwegian market, shifting their focus abroad. This was recently substantiated in an announcement from Statkraft AS and StatoilHydro, two of Norway's largest power companies; they are merging forces on a 315 MW UK project (StatoilHydro, 2009).

50 km off the Norwegian coast water depths are normally in the range of 100 to 300 meters. Wind turbines located in those areas would generate 30% more energy than the turbines

in the Danish offshore wind farm Horns Rev 1 in terms of the same installed capacity due to higher average wind speeds further off the Norwegian coast than west of Denmark (Sway, 2009). Some of these resources can be accessed by deep-water seabed-founded wind turbines, but not all, and hence there are presently three different floating wind turbine concepts on the drawing boards of Norwegian offshore and energy specialised companies, carrying out the governmental wish of industrial development connected to offshore wind power (Norwegian Energy Council, 2008):

- StatoilHydro has decided to build the world's first full-scale floating offshore wind turbine, Hywind, and test it over a two year period offshore Karmøy in southern Norway. The jacket has recently been transported to Karmøy and the mounting will take place during the summer of 2009 (Teknisk Ukeblad, 2009).
- Sway does like Hywind feature a single floating turbine and they want to place a full-scale prototype outside Karmøy as well. NVE is considering the concession application as this is written (Sway, 2009).
- The third concept, WindSea, stands out from the others by having three turbines placed on each corner of a triangular platform. The constellation is chosen since the developers believe the wind plant will be more stable than other single turbine floating concepts, and since installation, maintenance and repairs can be carried out more efficiently (WindSea AS, 2009).



**Figure 1** Illustration of WindSeas' floating offshore wind turbine concept

One argument against wind power in Norway has been the harsh natural environment, especially in the north. It's therefore worthy to mention that failing components is still the dominant cause of production disruption in Norwegian wind farms, while weather conditions play a subordinate role (NVE, 2008). The link between component failures and weather is however absolutely present.

### **2.2.4 Status check on Mid-Norway wind power**

The term Mid-Norway isn't only used in this thesis but also in a considerable number of papers

describing the power challenges of the region. It's a generic term that is geographically and electrically more or less congruent with the three counties Møre og Romsdal, Sør-Trøndelag and Nord-Trøndelag south of Tunnsjødal. Mid-Norway will, as the introduction to this chapter states, be given special attention in this thesis (ref. chapter 4) and so its wind resources and its part in the Norwegian wind power play will be described separately in this subchapter.

#### 2.2.4.1 Mid-Norway wind resources

Half of Norway's offshore wind resources are found in the three northernmost counties, but Mid-Norway houses a substantial part of the remaining. An NVE study summarised these resources and the results are presented in (NVE, 2003). It shall be noticed that the figures include the total potential in Nord-Trøndelag whereas the hereby used definition of Mid-Norway doesn't include the uppermost part of the county (north of Tunnsjødal).

County	< 10 m	< 20 m	< 30 m	< 40 m	< 50 m
Møre og Romsdal	21.0	43.6	62.8	76.1	96.9
Sør-Trøndelag	17.1	33.6	44.7	51.8	63.5
Nord-Trøndelag	22.5	41.9	57.6	71.4	86.5
	<b>60.6</b>	<b>159.1</b>	<b>175.1</b>	<b>199.3</b>	<b>246.9</b>

**Table 1 Constructionable offshore wind power resources in Mid-Norway. The resources are given in TWh/year and presuppose construction on water depths that are less than given in the upper row. The figures do only include resources that are within a distance of 40 km from the shore.**

The potential for offshore wind power presented in Table 1 include resources on depths that aren't economically profitable with the monopole solutions of today, but there are market operators who claim that they can construct seabed-founded wind turbines on depths up to 200 meters (Blue H, 2009).

Another approach to an insight into Mid-Norway's wind resources is by looking at the region's average wind speeds. Such data can be accessed through The Norwegian Meteorological Institute's (NMI) open access online climate observation database eKlima (NMI, 2009). eKlima contains observations from several sea based Mid-Norway observation stations, and average wind speed data were sorted for a selection of three of these. The three observation stations are all located at remote lighthouse islands in Mid-Norway in the middle of their respective counties. Sula is located approximately 120 km north of Ona and 120 km south of Nordøya and all three stations are located around 10 km off the nearest obstructing peninsula or island. The data are collected during a six-year period and the heights refer to anemometer altitudes above sea level. The results are presented in Table 2.

Observation station	County	Height [m]	Average wind speed [m/s]
Ona	Møre og Romsdal	13	7.6
Sula	Sør-Trøndelag	5	6.6
Nordøya	Nord-Trøndelag	33	9.0

**Table 2 Average wind speed measurements from three selected observations in Mid-Norway. The average wind speeds are based on daily average wind speed measurements from the 1.1.2003 to 31.12.2008. The height refers to the anemometer height.**

The wind speed differences may be attributed to different wind regimes in the three areas, local obstacles around the measurement points and/or the wind gradient, i.e. the effect of earth surface friction on wind which causes an exponential wind speed increase with raising altitudes. Other sources for the variations may also exist, but there is reason to believe that the effect of wind variations with heights is a primary source to the average wind speed differences. The phenomena is well documented, see for instance (Wizelius, 2007). The project group behind the Havsul 1 project (ref. chapter 2.2.4.3) located a few km southwest of Ona lighthouse estimated a wind speed of about 8 m/s at 50 meters height by merging Ona wind speed measurements with measurements at the nearby onshore wind farm Harøy (Havgul AS, 2006). The sampling times of these data acquisitions haven't been given. As a conclusion does the average wind speeds at hub height appear likely to be adequate for wind farm constructions along most of Mid-Norway's coastline.

eKlima also contains wind direction measurements for the observation stations. The wind direction measurements strengthen the impression of a generally favourable Mid-Norway wind regime; the wind conditions are characterized by two opposing main wind directions, with south-western winds blowing more than a third of the year and a severe trend of north-north-eastern winds (NMI, 2009).

### ***2.2.4.2 Existing Mid-Norway wind farms***

Mid-Norway wind farms are dominating the Norwegian wind power scene. At the end of 2008 there were 18 wind farms in Norway with a total installed capacity of 428 MW (EWEA, 2009). Around three quarters of this capacity was in Mid-Norway, including: Smøla 1&2 (150 MW), Hundhammerfjellet (37.5 MW), Bessakerfjellet (57.5 MW) and Hitra (55 MW). Smøla accounts for nearly half of Norway's wind power generation alone (IEA Wind, 2008, pp. 203-208).



**Figure 2** Statkraft's wind farm at Smøla.

### **2.2.4.3 Prospective Mid-Norway wind farms**

The wind farm licensor in Norway, NVE, has granted two new wind power projects concession in Møre og Romsdal. One of them, Havsul 1, will, if local natural preservation argued appeals are rejected and construction actually takes place, be Norway's first offshore wind farm. The other project is the 66 MW onshore wind farm Haram.

From a Norwegian perspective, the Havsul 1 project is gigantic with its installed power of 350 MW (Havgul AS, 2006). Commissioning of wind farms of any size would improve the pressed Møre og Romsdal power balance situation, and so NVE has decided to give Møre og Romsdal located wind farm projects top priority at their concession management department (NRK, 2008) in accordance with their priority practice (NVE, 2008). The two other Havsul projects have nevertheless been turned down by NVE under the argument that they want to investigate the environmental consequences of Havsul 1 prior to handing out other offshore wind farm licenses in Møre og Romsdal. Hence, the remainder of the 1500 MW Møre og Romsdal offshore wind farm portfolio NVE was considering (Norvind, 2008), will, when disregarding Havsul 1, not be considered until NVE regards their data collection from Havsul 1 as satisfactory.

Two scenarios have been imagined in the short term voltage stability and power balance simulations of chapter 7, viz. a case where the 350 MW project Havsul 1 has been commissioned and a (even more) futuristic one where additionally 650 MW of offshore wind power has been commissioned in Mid-Norway, bringing the total offshore wind power generation capacity of the region to 1000 MW in all.

The onshore wind farm construction rate is expected to be low over the next years (IEA Wind, 2008).

### 3 Hydro and wind power generation characteristics

There is an essential difference between traditional hydro power plants and wind turbines: Power production in a hydro power plant can be carried out whenever desired whereas wind turbines can only produce electricity when there is wind. The differences between electricity production in hydro power plants and wind turbines are stressed in the two subchapters, which (Machowski, et al., 1997, pp. 17-25) and (Söder, et al., 2005, pp. 25-51) have been key sources to.

#### 3.1 Power output from hydro power plants

Water above sea level has kinetic energy. This is turned to account in both Pelton (impulse type) and Francis (reaction type) hydro turbines which are the two most common types of turbines in Norwegian hydro power plants; water is led from a high levelled reservoir through a penstock to the hydro turbine where the kinetic energy is converted into mechanical energy. In the impulse turbine the kinetic energy that is available in the water is converted into mechanical energy as the water passes through the nozzle, while in the reaction turbine some of the kinetic energy of the water is converted into mechanical energy as the water passes through the wicket gates and the rest is converted inside the runner itself. The power output is controlled by regulating the water flow in the turbine by adjusting the position of the needle in the impulse turbine and the angle of the wicket gates in the reaction turbine. Both the impulse turbine needle and the reaction turbine wicket gates do in that way work as valves. The mechanical energy causes the turbine wheel to rotate and this rotational movement is transferred to the generator by the main shaft. The generator end of the main shaft rotates inside the generator and this movement causes electric power to be generated in the generator stator.

The power output ( $P$ ; MW) from a hydro power plant is thus dependent on pressure height or head ( $H_N$ ; m), mass flow of water ( $Q$ ; m<sup>3</sup>/s) in addition to the nature-given parameters. The power output is expressed in equation 3.1 where ( $g$ ; m/s<sup>2</sup>) denotes the gravitational constant, ( $\rho$ ; kg/m<sup>3</sup>) water density and ( $C_p$ ) total power efficiency. This amount of power can be produced as long as there is water in the reservoir, although the net head and accordingly the power output may vary slightly.

$$P = H_N \times Q \times g \times \rho \times C_p \quad (3.1)$$

Norwegian grid connected hydro power plants with rated power larger than 10 MW shall reach their nominal rating within 1-4 minutes from cold start (Statnett, 2005).

#### 3.2 Power output from wind turbines

Wind has kinetic energy since wind is formed by air movement and air has mass. The conversion process from turbine rotation to power generation in the generator stator is similar to the one for hydro turbines (ref. subchapter 3.1); it is the turbine drivers that differ; water and wind.



Equation 3.2 shows the formula for kinetic energy, where ( $m$ ; kg) is mass and ( $v$ ; m/s) velocity.

$$E = 0.5 \times m \times v^2 \quad (3.2)$$

The kinetic energy equation can be converted into a flow equation as shown in equation 3.3. The equation shows power in the area swept by the rotor, where ( $P$ ; MW) denotes power, ( $\rho$ ; kg/m<sup>3</sup>) air density, ( $A$ ; m<sup>2</sup>) swept rotor area and ( $v$ ; m/s) wind speed.

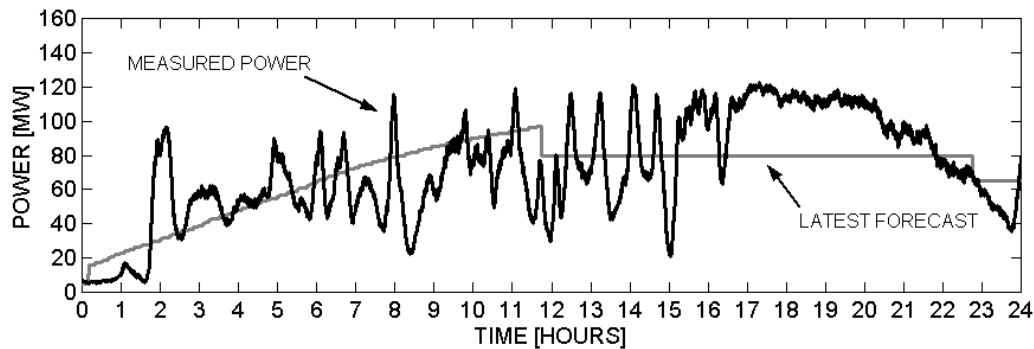
$$P = 0.5 \times \rho \times A \times v^3 \quad (3.3)$$

Multiplying the last equation with the total turbine power efficiency gives the total wind turbine power in equation 3.4, where ( $C_p$ ) denotes total turbine efficiency.

$$P = 0.5 \times \rho \times A \times v^3 \times C_p \quad (3.4)$$

This leads to some challenges for the TSO of a power system of which the power generation is partly based on wind turbines. As equation 3.4 shows wind speed variations imply power output variations and the power output is zero when calm.

The Danes have acquired power generation knowledge from offshore wind farms since they commissioned the world's first offshore wind farm 1991, namely the 5 MW Vindeby. A common expectation was that offshore wind conditions would be more stable and calm than onshore conditions since there are no obstacles on the open ocean as opposed to land sites, but their operation experience has shown something else. As an example, the power generation in Horns Rev 1 offshore wind farm which is located 14-20 km off the western coast of Denmark has sometimes been characterized by rapid, excessive, repeating-character fluctuations as shown in Figure 3.



**Figure 3** Expected (hourly-updated latest forecast) and measured (factual) power generation from the Danish offshore wind farm Horns Rev 1 as on August 31st, 2003, (with 120 MW in-service). The figure is reproduced from (Akhmatov, et al., 2009). The latest forecast is what the power balance responsible player applies for the power generation plan of the virtual power plant containing the wind farm and a number of thermal power plants in Western Denmark.

On top of the varying power output from the wind farm, there is a chance for another wind power attributed power balance challenge; sudden and forced shut-down. For safety reasons

and to reduce wear wind turbines are stopped and disconnected from the grid when the wind speed exceeds the so-called cut-off speed which usually is 25 m/s (10 minutes average).

The power generation data from Figure 3 are used in the simulations in chapter 7 (ref. chapter 6.3.5).

## 4 Power balance challenge area: Mid-Norway

The Norwegian TSO Statnett has published several papers on the power situation in Mid-Norway, because the region stands out in Norway as the one where they are most concerned about their ability to execute their task of assuring safety of supply in the future. At the same time, the area has got great wind resources and more than half of the yearly wind power production in Norway. A relatively large expansion in installed wind power capacity in the region is one possible way to meet the power demand deficit by regional production within the next decade and also in a longer perspective.

The bus bar representing Mid-Norway in Sintef's simplified grid model (ref. chapter 6.1) has been chosen as the bus bar to which the offshore wind farm will be connected (ref. chapter 6.3). The main reasons for this choice are outlined in the above paragraph and will be given a deepened account for in this chapter.

(Ministry of Petroleum and Energy, 2008), (Statnett, 2006) and (Statnett, 2007) are key sources to this chapter.

### 4.1 Power balance in Mid-Norway

According to (Statnett, 2007), Mid-Norway in general and Møre og Romsdal in particular has the largest power deficit in the country today with respect to installed power capacity, and the report predicts the power balance situation to worsen furthermore in the coming years. Several large industrial projects have been commissioned the last decade without increasing the generation capacity correspondingly and the transmission system have until the latest years not seen the necessary strengthening actions either.

Mid-Norway's power-intensive industry accounts for nearly half of the region's power demand, and the industrial power consumption is predicted to increase furthermore in the coming years. Major industrial projects in the area include construction of the onshore process terminal for the gas field Ormen Lange at Nyhamna in 2007, the 2004 modernization of the aluminium works at Sunndalsøra and a planned expansion of Hustadmarmor AS located at Fræna in 2010. Partly as a result of this, Mid-Norway's energy consumption is expected to increase with nearly 3.5 TWh/year between 2007 and 2020, i.e. around 17%. About 20 TWh/year is consumed in Mid-Norway in an average year, which is a little less than the predicted consumption for 2009, i.e. 22.5 TWh/year. Comparing this to the average yearly power production, which in an average precipitation year is 13 TWh, reveals an average Mid-Norway energy deficit of 7 TWh/year. This means that approximately one third of Mid-Norway's energy demand must be covered by import from Sweden and other parts of Norway. If the prognosis are correct and no actions are addressed to reduction of this energy deficit by commissioning of new generation capacity, today's 7 TWh yearly energy deficit will increase to 9 TWh in 2015 and 10 TWh in 2020. Statnett estimated the region's maximum import capacity, as an attempt to quantify the challenges, and the theoretical maximum was found to be 8-10 TWh/year, whereas the highest actual import was 7.5 TWh in 2006. The maximum import capacity will increase to 10-12 TWh/year by the end of 2009 (ref. subchapter 4.2).

Statnett fears that a continuation of today's trend of a yearly demand increase will lead to a situation within a few years where they cannot meet the regions demand for electricity if no actions are addressed to strengthening the region's transmission system. A number of bracing actions and initiatives have therefore been proposed or already effectuated by Statnett, as subchapter 4.2 will deepen.

## 4.2 Mid-Norway transmission system

As subchapter 4.1 accounts for, the Mid-Norway power transmission system of today won't be able to handle the region's anticipated future power deficit in a satisfactory way. As Statnett's top priority is to see to that all Norwegian consumers have a reliable supply of power, they have carried out several strengthening initiatives directed to the transmission system in Mid-Norway. Subchapter 4.1 also briefly mentions that a large part of Mid-Norway's power balance challenges in fact are challenges specifically attributed to the county Møre og Romsdal. A majority of Statnett's efforts have therefore taken place within Møre og Romsdal, with the main purpose of raising the maximum voltage level from 300 kV to 420 kV. Already executed actions include construction of new overhead lines, upgrading of 300 kV lines to 420 kV lines and commissioning of new transformer stations.

With the recent constructions and upgrades Statnett considers the transmission system within Møre og Romsdal adequate with respect to the anticipated nearest future power balance. The new 420 kV Nea-Järpstrømmen connection to Sweden will in this manner contribute substantially from the autumn of 2009 when it is to be commissioned. With the new connection to Sweden and other already executed actions Statnett estimates that Mid-Norway's import capacity by the end of 2009 will have increased from 8-10 to 12 TWh/year compared to 2004.

While the internal Møre og Romsdal transmission system is becoming adequate, inter-area transmission capacity increases are nevertheless regarded as necessary to meet the challenges of a reliable long term power supply. This includes both connections from Møre og Romsdal to the other parts of Mid-Norway and connections from Mid-Norway to the surrounding regions. A final piece in the Mid-Norway power balance jig-saw puzzle can in that respect be Statnett's proposed 420 kV transmission line from Ørskog in Møre og Romsdal to Fardal in Sogn og Fjordane. The line, which can be commission no earlier than 2013, will increase mid-Norway's import capacity additionally to a total of 15-16 TWh/year. Although NVE has recently accepted the concession application and there is a pressing need for grid reinforcements at the 400 kV level, it seems unlikely to see its birth within the nearest future because the suggested trace passes through several protected natural zones. Local authorities will therefore probably appeal the concession again, delaying the construction furthermore. The Ørskog-Fardal voltage line would in addition to the primary positive effects on the Mid-Norway power balance also involve some side effects like better Sogn og Fjordane security of supply and transmission capacity. This would again open new wind power doors, as wind farm constructions in Sogn og Fjordane are restricted not only by concessional and financial challenges but also by transmission constraints.

The power situation in Mid-Norway was more pressed a couple of years ago than now, and so in 2006 Statnett introduced Mid-Norway as a third price zone (Norway is normally split in two price zones, i.e. North and South) as a mean to increase the consumption controllability. In

November 2008, Statnett decided to unite Mid-Norway and North-Norway as a price zone again, and today Statnett class the power situation in Mid-Norway as acceptable.

## 5 Power system frequency, secondary control schemes and FRT

Electricity cannot easily and inexpensively be stored in large quantities, and so balancing power generation with power consumption is an exercise present in all electrical power systems. The balancing task is specially challenging for a system with a high level of wind power penetration, since wind power is a source of uncertainty with respect to anticipated generation (ref. chapter 3.2). For Norway's part, the task is particularly challenging in Mid-Norway because the area on top of having the country's largest share of wind power also is burdened with lack of production capacity and transmission constraints (ref. chapter 4).

Changes in demand (and/or supply) in a power system can be observed by measuring the system's frequency; an increase in demand will result in a frequency decrease and vice versa. The TSO is responsible for the important task of maintaining a stable system frequency, and in this exercise, hydro power plants and wind farms are because of their generation characteristics (ref. chapter 0) hand in glove working partners. These circumstances meet in the main objectives of this thesis (ref. **Feil! Fant ikke referansekinden.**).

This chapter gives an introduction to the theory that is necessary to know to understand the chapter 7 simulations. Power system frequency during normal operation is initially explained together with the basic principles of Load Frequency Control (LFC), since LFC is implemented as secondary control in the Nordel synchronous system model of chapter 6. LFC is used in the Union for Co-ordination of Transmission of Electricity (UCTE; Nordel's sister organization in Europe), but not in the Nordel synchronous system, where the simulations take place. An explanation on how the secondary control is carried out in the Nordel synchronous system is therefore given in subchapter 5.3 together with an explanation on why it has been chosen to implement LFC as secondary control in this thesis. In order to understand the fault ride through simulations presented in chapter 7.1.2 and 7.2.2, some brief theory on the importance of spinning reserve and fault ride through are presented towards the end of the chapter.

This chapter is mainly based on (Bakken, 1997), (Nordel, 2007, pp. 70-73) and (UCTE, 2004).

### 5.1 Nordic synchronous area system frequency

The Norwegian TSO Statnett is partner in a Nordic central distribution system collaboration organisation called Nordel. Nordel was constituted in 1963 and consist of the Nordic TSOs, i.e. Statnett in Norway, Svenska Kraftnät in Sweden, Energinet.dk in Denmark, Fingrid Oyj in Finland and Landsnet hf in Iceland. It's an advisory and recommendatory organisation which is entrusted with the task of contributing to an efficient electrical power system, taking into account the conditions prevailing in the different countries. Nordel aims among other things for a robust transmission system with few large price areas, security of supply, efficient resource usage across borders and a liquid and transparent electricity market in North-Western Europe (Nordel, 2009).

The goals are reflected in Nordel's tasks, which concern system operation and reliability, security of supply, determination of technical recommendations etc. From time to time, Nordel also draws up a set of rules to govern the operation and development of the Nordic countries' power system, with the purpose of "...achieving uniform and coordinated Nordic operation and

planning between the TSOs in order to establish favourable conditions for the development of a well-functioning and effectively integrated Nordic electricity market” (Nordel, 2009). The set of rules is called the Nordic Grid Code (NGC) and the latest version is dated 2007.

The NGC defines the Nordic synchronous system as “...the synchronously interconnected power system consisting of the subsystems of Norway, Sweden, Finland and Eastern Denmark” and normal operation as “...an operational state entailing that all consumption requirements are being met, that frequency, voltage and transmission lie within their limits and that reserve requirements are being met. The system is prepared to deal with dimensioning faults” (Nordel, 2007). Dimensioning faults in this context are “...faults which entail the loss of individual major components like for instance bus bars, lines or generation units and entail the greatest impact upon the power system from all fault events that have been taken into account”. During normal operation the requirement of the highest permissible variation in frequency during normal state is between 49.9 Hz and 50.1 Hz in the Nordic synchronous system. A constant frequency of 50.00 Hz is what the Nordel TSOs are continually aiming at.

A reliable and stable power system with a defined value of frequency and low frequency fluctuations is crucial for optimal performance of the components in a power system, and this is reflected in the NGC where prevention of frequency excursions is regarded as the number one priority with respect to the power quality standards (Nordel, 2007, p. 74). The ability to keep the frequency within desired limits is thus a key indicator of a power system’s operating reliability and power balancing control performance. Some technical equipment is especially vulnerable to frequency excursions; steam turbine blades are for instance designed to operate in a narrow band of frequencies. Deviation of frequency beyond this band may cause gradual or immediate turbine damage and automatic disconnection of generators, and this may consequently cause financial revenue decreases and at worst power system collapses (Prasat, 2006).

The NGC also defines power balance as “...equal power consumption and generation” and Momentary Control Error (MCE) as “...the disparity (in MW) between the sum of the measured power and the sum of the agreed exchange plan on the links between the subsystem plus frequency correction, which is the subsystem’s momentary frequency response multiplied with the deviation in the frequency away from 50 Hz”. MCE is also called the momentary imbalance. Momentary disturbances in the power balance between mechanical power output from the turbines and the electrical demand are normally cleared without the need to reduce the generated or consumed power. Sudden connections or disconnections of generating units or large loads will however result in an imbalance between produced and consumed power and such a power imbalance will result in a change in frequency. Subchapter 5.3 will explain how regulating power is used in the Nordic countries to prevent such frequency excursions.

## 5.2 Load frequency control

The power demand of an electrical power system must at all times be met by a corresponding and instant power generation. This may in principle look like an impossible task, but as one moves from the distribution system to the transmission system and loads are aggregated the change of demand is smoothed, making it possible to predict the demand quite accurately. With a large system, weather forecasts and well-known day to day and seasonal demand variation patterns, the

power demand can be met more or less by a scheduled generation pattern. Disparities between generated and consumed power are cleared by regulating control mechanism, which in many countries include the so-called LFC.

Definitions of the primary and secondary control are needed to understand the theory behind LFC, but since their definitions vary dependent on who set them, general consideration on what they involve are proposed, based on (UCTE, 2004):

- The objective of primary control is to maintain instantaneous balance between generation and consumption in a synchronous area by using turbine speed or turbine governors. Primary control is fast actions (time frame of seconds) made by the speed-governor aimed to re-establish power balance and stabilise the system frequency at a stationary value after a disturbance, without considering restoration of the system frequency reference value or power exchanges.
- Secondary control replaces primary control after minutes. It is slow (time frame of minutes) control actions with the purpose of re-establishing the system frequency and scheduled power interchanges at their reference values after a deviation, by adjusting generators' set-points. Secondary control also seeks to restore the primary control reserves (i.e. available generation capacity to be used in primary control), and is in several power systems (including UCTE) congruent with LFC. The secondary control reserve is the difference between the operating point and the maximum available secondary control capacity.

Primary and control actions respond continually to minor deviations that inevitably occur during normal operation and secondary control actions to major discrepancies between generation and consumption caused by e.g. fall-out of transmission lines or tripping of generators. The control scheme sketched above fits the operation practice of UCTE. In UCTE, both the primary and the secondary control are fully automated and the secondary control is implemented as LFC, while in Nordel, the primary control is fully automated, but the secondary control is partly handled manually. This is more thoroughly described in subchapter 5.3.

As the LFC scheme is common, easy to implement and well-suited for such analyses as the ones described in the presentation of the objectives of this thesis, the LFC scheme has been chosen as secondary control tool for the chapter 7 simulations, in spite of not being used in the Nordel synchronous system. Subchapter 6.7 explains how the LFC is implemented in the Nordel synchronous system model.

Neither the primary nor the secondary controls embrace any pecuniary motives. This is introduced in a third control level; tertiary control, which re-establishes the secondary control reserves and re-dispatch the secondary control reserves between different machines to obtain a more economical operation. Tertiary control isn't given any attention in this thesis.

### **5.2.1 Generation plans in Nordel**

In general, production planning entails the acquisition and allocation of limited resources to production activities to satisfy a demand over a specified time horizon. Production planning is thus inherently an optimization problem, where the objective normally is to develop a plan that meets demand at minimum cost or that meets demand and maximizes profit.



The same principles pass for power generation planning in electric power systems, and in Nordel, the objective is to meet the electric power consumption at the lowest cost (Nordel, 2007, p. 16). To optimize the power exchange between the members of the Nordel co-operation, generation plans are updated and followed up each hour by power plants and HVDC links according to the anticipated demand forecast (see subchapter 6.5 on HVDC technology). In some parts of the Nordel synchronous system, so-called *load following* has been introduced, entailing that market players with major production changes report production changes with a resolution of 15 minutes. Increasing the time frame resolution is done to improve the quality of the frequency throughout the synchronous system. All exchanges are made specifying the power, price, link and time to the exact minute of the start and finish of the exchange.

The hourly procedures in this following paragraph also apply to the quarter-hourly power shifts. The hourly power shifts of the power plants starts 5 minutes ahead of each hour to comply with the received generation plans. Then, the generation plans must be completed by the groups of power plants in no longer than 10 minutes. The total power generation from the power plants is adjusted to follow the plan in a period from -5 to +5 minutes at each hourly shift. The hourly power transmission plan is distributed to the HVDC links 5 minutes ahead of each hour. The power exchange through the HVDC links is, then, ramped in the following 10 minutes to meet the received plan. This means that the power exchange through the HVDC links is adjusted in a period from -5 to +5 minutes at each hourly shift.

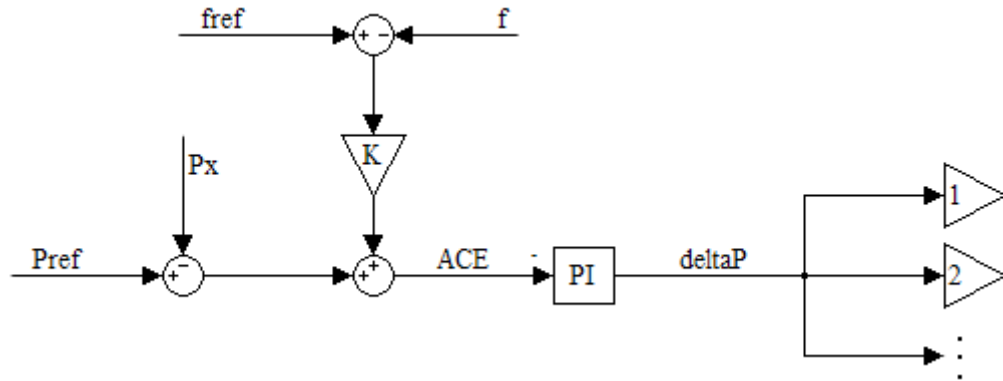
Commissioned wind power clearly affects the generation plans (ref. subchapter 3.2). The amount of wind energy that is available at a given time is obviously independent of the forecast, and so wind power has value even if forecasts aren't accurate. But as wind farms are becoming more economically competitive with conventional energy sources, it's important to correctly assess the capacity value of wind; wind resources that cannot be counted on for capacity has minimal contribution to system reliability. Unexpected wind power can still be used to displace energy that is provided by a load-following unit, but an accurate forecast allows the utility to count on wind capacity, reducing costs without violating reliability constraints. Studies have shown that accurate wind forecasts have severe economical benefits, see e.g. (Milligan, et al., 1995).

This subchapter is based mainly on (Akhmatov, et al., 2009, p. 45) and (Nordel, 2007).

### **5.2.2 Basic theory of LFC**

To understand the basic theory of LFC, the terms Control Area and Area Control Error (ACE) need to be defined. According to UCTE definitions, a control area is the smallest portion of a power system equipped with an autonomous LFC, and the ACE is a measure of a control area's deviation from agreed power interchange with its neighbours, compensated for the area's activated primary control reserves. In others words, the ACE is the difference between scheduled and actual power generation within a control area. Negative values denote a condition of under-generation and positive values denote over-generation (UCTE, 2004, p. 8). In UCTE, the so-called frequency control error (equal to the product of the frequency deviation and a gain factor) contributes in determination of the ACE, but the contribution from the frequency control error has been omitted in the implemented LFC scheme in this thesis for simplicity reasons.

Fully automated LFC is a well-known and rather simple way to handle secondary control; the control equipment and design procedure for classic LFC is standard, easily manageable for practical implementation and has been used successfully for many years. Presuming that enough generation capacity is available, LFC will handle all deviations in the system, including normal load changes, HVDC ramping and faults. In brief, LFC is slow adjustments in generating units' operating points in the range of minutes to re-establish nominal frequency and scheduled interchanges after a deviation. For the conventional control strategy of the LFC problem, the adjustments are based on integration of the ACE. The classic LFC setup is shown in Figure 4.



**Figure 4 Classic LFC setup.** The ACE as it is defined in (UCTE, 2004) is calculated from the area interchange setpoint, the momentary area interchange, the momentary system frequency, the reference frequency, and the area frequency bias setting, denoted  $P_{ref}$ ,  $P_x$ ,  $f$ ,  $f_{ref}$  and  $K$  respectively.  $P_x$  and  $f$  are variables of time. The ACE is then used as control signal in the PI controller. The PI controller returns the additional power demand signal ( $\Delta P_d$ ) which is sent to the selected generating units 1, 2 ... n ( $P_1$ ,  $P_2$ ... in the coming paragraphs). The ACE and  $\Delta P_d$  signals are also variables of time.

Figure 4 yields the definition of the ACE as it's defined in equation 6.1, by means of the net area interchange deviation ( $\Delta P(t)$ ; MW), the frequency bias setting ( $K$ ; MW/Hz) and the system frequency deviation ( $\Delta f(t)$ ; Hz).

$$ACE(t) = \Delta P_x(t) + K\Delta f(t) \quad (5.1)$$

Figure 4 also yields equation 6.2 which shows how the extra power demand signal ( $\Delta P_d(t)$ ; MW) that is sent to the designated generating units ( $P_1$ ,  $P_2$  ...) is determined by integration of the ACE. ( $T_I$ ) denotes the integral time constant of the Proportional-Integral (PI) controller and ( $K_p$ ) the proportional gain.

$$\Delta P_d(t) = -K_p ACE(t) - T_I \int ACE(t) dt \quad (5.2)$$

The feedback controller is chosen of the PI type in order to have no residual error. The integral term must also be limited in order to have a non-windup control action, able to react immediately in case of large changes or a change of the sign of the ACE. By recommendations of the UCTE, the proportional gain constant is in the range of 0-0.5 pu (referring to the size of the ACE) and the integral time constant is in the range of 50-200 seconds (UCTE, 2004, p. 11). UCTE's recommended ranges of values for the variables in the PI controller are set in order to

ensure a smooth operation and to prevent interference between the LFC and the primary control. The PI controller also includes boundary limitations.

Within UCTE three different schemes of active power and frequency control are applied:

- Centralized LFC scheme, where one such regulating and centralized controller as shown in Figure 4 is responsible for handling the ACE of the whole country. This centralized LFC model is found in e.g. Austria and the Netherlands.
- Decentralized LFC schemes of two kinds: the hierarchical and the pluralistic. LFC is in the decentralized structure carried out by separate controllers of a country's control areas that are subordinate to a superior national controller named coordinator, and so each control area is thus responsible for handling its own cross-border power exchange while the national controller handles the interchange with other countries. In the pluralistic scheme the coordinator controls the power flow through the cross-borders of the entire control block, while the other control areas separately control their own cross-border exchanges. In the hierarchical scheme the coordinator affects all the separate control areas for controlling the power flow at the cross-border of the entire block. The pluralistic scheme is utilized in e.g. France, Portugal and Spain, with France as coordinator, and the hierarchical model in e.g. Switzerland (Dell'Olio, et al., 2005).

The decentralized LFC model is more secure than the centralized, but considerably more complicated to implement, according to (Bakken, 1997, pp. 191-200). Finally, it is also worthy to mention that LFC is often in conflict with economic power dispatching (which is at first introduced on the next, i.e. tertiary, control level).

### **5.3 Regulating power for secondary control in the Nordel synchronous system**

The Nordel synchronous system has for several decades been operated in a decentralized way. The power plants follow daily generation plans that are results of Nord Pool Spot bilateral contracts, and the TSOs have little information about the generation at the different units in the planning stages (Nordpool, 2009). Hence, there is no centralized optimization.

While some traditional ancillary services like e.g. primary control (governor droop), load shedding and reactive support are mandatory (some of the services are however compensated for economically), secondary control has been fully market based since the deregulation of the market in 1991. Power companies can participate in the regulating power market either by entering into agreements with the TSOs on availability obligations and settlements or by placing regulating power bids on the power exchange whenever the company finds it attractive. The power company will in both cases receive payment for the provided regulating power, but also availability compensation in case of availability obligation. The regulating power bids are then aggregated and sorted by price by the TSO, who chooses objects from this list according to price when regulations are necessary. Whenever unforeseen imbalance between production and consumption occur, the TSOs of each area will then manage it by contacting generators or system control centres by phone, requesting for manual activation of their offered regulating power to

clear the unexpected power deviations. With this in mind, the Nordel synchronous system does ergo not apply any automatic secondary control scheme like LFC. The secondary control function as defined in subchapter 5.2 is all the same present in the Nordel synchronous system as well; divided into the so-called automatic active and manual active reserves that are to be described closer in this subchapter. The description active owes to the fact that the reserves constitute parts of the active power balance reserves. The NGC also presents regulations for the reactive power reserves, but reactive power considerations are not treated in this thesis, and hence those regulations aren't presented. The term secondary control isn't used in Nordel.

This subchapter shows the layout of the secondary control reserves. It's put together in the same way as the classification in (Nordel, 2007) and includes stipulated amounts, activation instructions etc. for the power balance reserves in the Nordel synchronous system. The structure and the terms are generally taken from (Nordel, 2007), but some definitions and explanations are somewhat shortened or deepened to the NGC.

### **5.3.1 Automatic activated reserves**

The Automatic Activated Reserves (AAR) consist of the Frequency Controlled Normal Operation reserve (FCNOR) and the Frequency Controlled Disturbance Reserve (FCDR). The major parts of both the FCNOR and the FCDR shall be achieved via automatic frequency regulation in production units, and the requirements shall be met by putting demands on the turbine regulator settings, or more precisely the regulating time constants. The requirements on the FCNOR and the FCDR are deepened in the subchapters 5.3.1.1 and 5.3.1.2.

#### **5.3.1.1 Frequency controlled normal operation reserve**

The Frequency Called Normal Operation Reserve (FCNOR) is used to avoid frequency deviations in the Nordel synchronous system. The FCNOR shall be activated linearly until the full reserve is utilised for a frequency deviation of 0.1 Hz with 50 Hz being the reference value. In the case of rapid frequency changes, the FCNOR shall be activated within 2-3 minutes and at 50 Hz the FCNOR shall be at least 600 MW for the Nordel synchronous system. Norway's part of this is 203 MW. At least 2/3 of the 203 MW shall be found within the Norwegian power system in case of splitting up and island operation. The magnitude of the FCNOR is based on previous year's power consumption.

#### **5.3.1.2 Frequency controlled disturbance reserve**

The second part of the AAR is the FCDR. It is defined in the NGC as "... a reserve of such magnitude and composition that dimensioning faults won't entail a frequency of less than 49.5 Hz in the synchronous system". Dimensioning faults are defined in subchapter 5.1. The FCDR shall amount to an output power equal to the dimensioning fault minus 200 MW and it must be available for usage until the FADR (ref. subchapter 5.3.2.2) has been activated. Norway's part of the FCDR is 317 MW. As it is in the FCNOR case, 2/3 of Norway's FCDR responsibility shall also be within the Norwegian power system in the event of splitting up and island operation. The FCDR shall be activated at 49.9 Hz and increase linearly until the reserve is completely activated

at a frequency of 49.5 Hz. In the case of a momentary frequency drop to 49.5 Hz caused by momentary loss of production 100% of the FCDR shall be regulated upwards within 30 seconds.

### **5.3.2 Manual active reserves**

The manual active reserve is the active reserve which is activated manually during the momentary operational situation. This is divided into the fast active forecast reserve, the fast active disturbance reserve, the fast active counter trading reserve and the slow active disturbance reserve.

#### **5.3.2.1 Fast active forecast reserve**

The fast active forecast reserve is the manual active reserve for regulation of forecasting errors for consumption and production.

#### **5.3.2.2 Fast active disturbance reserve**

The fast active disturbance reserve is the manual reserve available within 15 minutes in the event of the loss of an individual principal component (production unit, line, transformer, bus bar, etc.). The fast active disturbance reserve shall restore the frequency controlled disturbance reserve.

#### **5.3.2.3 Fast active counter trading reserve**

The fast active counter trading reserve is the manual active reserve for carrying out counter trading. Counter trading is the purchasing of upward and sale of downward regulation, executed by a TSO in order to eliminate a bottleneck or in order to increase the trading capacity between two Nordpool Elspot Market areas.

#### **5.3.2.4 Slow active disturbance reserve**

The slow active disturbance reserve is the active power that is available after 15 minutes.

### **5.3.3 Emergency power**

In addition to the active reserves, an emergency power scheme is recorded. Emergency power can be activated both by automatic systems and manually, and, depending on definitions, both power regulation on HVDC links and load shedding can sort under this topic.

#### **5.3.3.1 Power regulation on HVDC links**

Emergency power is power regulation on HVDC links on both sides of the link. The regulations can either be activated by automatic systems or manually. In case of severe frequency drops the HVDC cables that connect the Nordel synchronous system to other synchronous power systems will gradually be activated for import of emergency power, until maximum capacity of all HVDC connections, i.e. 1200 MW, is utilised when the frequency passes 49.0 Hz downwards. It shall be emphasized that a DC installation that is performing a full import to a low-frequency area obviously isn't capable of contributing with more emergency power.

HVDC power regulation actions are also effectuated in the case of too high frequency, but in a correspondingly opposite way.

### 5.3.3.2 Load shedding

Load shedding is defined as "... automatic or manual disconnection of consumption" in (Nordel, 2007). Statnett business idea, viz. to arrange for a power market with a high security of supply (Statnett, 2009), is obviously more or less inconsistent with load shedding, but if frequency drops cannot be bridled by activation of the active reserves or by power regulation on the HVDC links, load shedding comes forth as the ultimate option.

Agreed automatic load shedding (in practice temporary disconnection of e.g. district heating or industrial consumption for economic compensation) can be used in the frequency range of 49.9 Hz to 49.5 Hz, but must in that case meet the technical requirements put on generators regarding linearity, time perspective etc. As severe frequency drops are dangerous as they may lead to system collapse, the means for preventing such drops are strong: Frequency drop between 49.0 Hz and 47.0 Hz will lead to load shedding of totally 7000 MW. This is done step by step at different frequency levels to allow the least important loads to be shed first. The 7000 MW amount is referred to a 2007 peak load situation (which was 21 589 MW (Nordel, 2009)).

For Norway, almost all load shedding occurs in the first seven weeks of the year, which due to the winter climate normally is the peak load period in Norway, but a milder climate has led to considerably smaller average load shedding over the last years than historically (Doorman, 2004).

## 5.4 The importance of spinning reserve

The following general definition of spinning reserve has been proposed by (Rebours, et al., 2005): "The spinning reserve is the unused capacity which can be activated on decision of the system operator and which is provided by devices that are synchronised to the network and able to affect the active power".

The importance of spinning reserve will be illustrated by an example and equations that are taken from (Machowski, et al., 1997, pp. 274-277): A 50 Hz ( $f$ ; Hz) system has got a total load of 10 000 MW ( $P_L$ ; Hz) in which 60% of the units ( $p$ ) give 15% of the spinning reserve (denoted  $r$  and defines the relative difference between the maximum power capacity of the system and the actual load). The remaining 40% of the units are fully loaded. The average droop of the units with spinning reserve is 7% ( $\rho$ ) and the frequency sensitivity coefficient of the loads is 1 ( $K_L$ ). If the power system due to a fault suddenly loses a generating unit of 500 MW ( $\Delta P$ ; MW), the frequency drop ( $\Delta f$ ; Hz) can be calculated by applying equation 5.4, but firstly the generation characteristic ( $K_G$ ) needs to be calculated, and this is shown in equation 5.3.

$$K_T = p(1 + r) \times \frac{K_L}{\rho} = 0.6 \times \frac{(1 + 0.15)}{0.07} \times \frac{1}{0.07} = 9.687 \text{ Hz} \quad (5.3)$$

$$\Delta f = \frac{-1}{K_G + K_L} \times \frac{\Delta P}{P_L} \times f = \frac{-1}{9.687 + 1} \times \frac{500}{10\,000} \times 50 = 0.23 \text{ Hz} \quad (5.4)$$

If there were no spinning reserve in the power system the power deficit would have been covered entirely by the frequency effect of the loads and the frequency drop would then be:

$$\Delta f = \frac{-1}{K_G + K_L} \times \frac{\Delta P}{P_L} \times f = \frac{-1}{0 + 1} \times \frac{500}{10\,000} \times 50 = 2.5 \text{ Hz} \quad (5.5)$$

Equation 5.5 shows that the frequency drop would be about ten times greater without spinning reserve compared to a case with 15% spinning reserve under the example's conditions.

The example shows how important it is to have spinning reserve in a power system. All four hydro power plants connected to bus bar 6500 (ref. subchapter 6.4) are grid connected and in production and have available capacity for upwards regulation, restricted only by power ratings and the upper boundary of the LFC. The available amounts can be read out of Table 3 on page 38.

## 5.5 Fault ride through

Wind power accounts for increasingly more of a modern power system's total generation, and since a high level of wind power penetration introduce significant impacts on operation of the on-land transmission system, the requirements put on new wind power projects are getting stricter and stricter. In Denmark, new offshore wind farms must contribute to the power system stability on a level with conventional power plants, constrained only by the limitations imposed at any time by the wind conditions in force. The requirements range from issues related to reactive power control and frequency response to the so-called Fault Ride Through (FRT) capability (Energinet.dk, 2004).

Production units play an important role in a power system during faults and operational disturbances in the grid; they shall contribute with short circuit capacity in order to ensure reliable clearance of faults and they shall provide for satisfactory after the fault clearance. On top of that, to maintain optimal system operation, production planners must know that production units don't disconnect in the case of grid faults. These requirements are known as fault ride through. The FRT requirements are listed in transmission system grid codes and define how big and how long lasting short circuit faults/voltage dips grid connected production units must endure before being allowed to disconnect from the grid. Figure 5 shows the prevailing FRT requirements in the Norwegian power system for production units connected to grids with level higher than 200 kV. As seen from the figure, production units shall, under the given voltage condition, bear a voltage drop to 0% for 150 ms (Statnett, 2008, p. 23).

FRT simulations on the Nordel synchronous system model are presented in chapter 7.1.2 and 7.2.1. In the simulations, various bus bars have been exposed to a 3-phase 100 ms. lasting short circuit fault, and the offshore wind farm has been subject to the prevailing requirements regarding FRT in Norway.

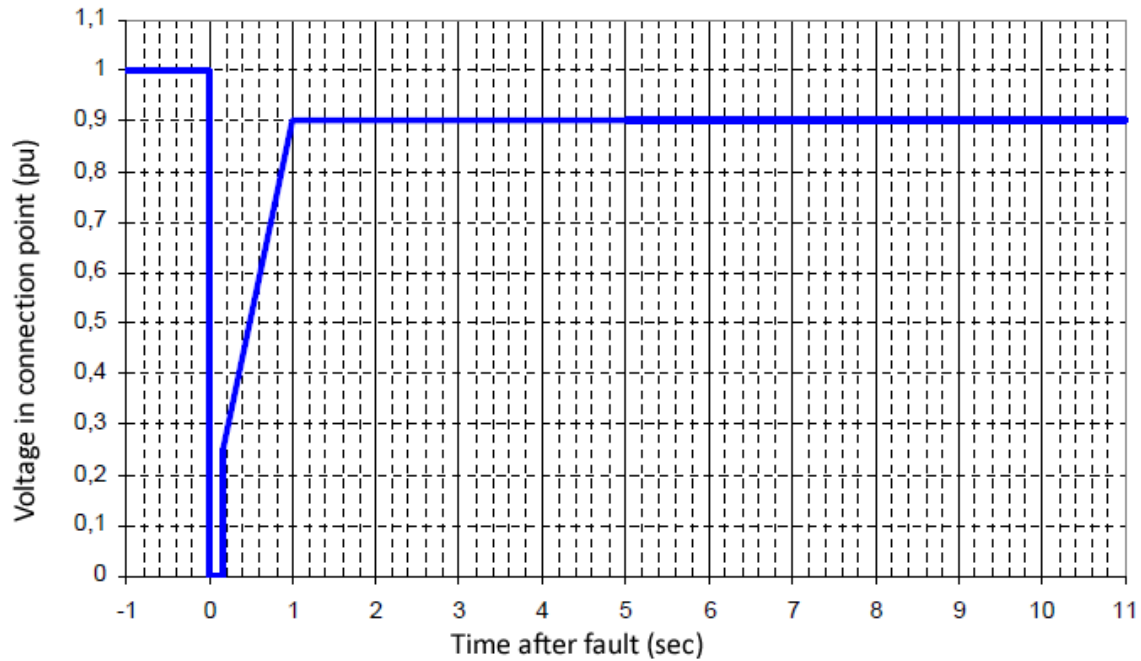


Figure 5 FRT requirements for grid connected production units in Norway. The figure shows that production units shall operate and deliver active power for at least 150 ms when the voltage level is 0%, followed by a voltage rise to 25% and subsequently a linear ascent to 90% within the next 750 ms. Operation and production shall then continue as long as the voltage remains above 90%. These specifications are valid for units connected to grids with a voltage level higher than 200 kV. The y-axis denomination pu is related to grid voltage level. The figure is reproduced from (Statnett, 2008)



## 6 Nordel synchronous system model

A model of the Nordel synchronous system developed and kindly provided by the Norwegian research organization Sintef has been used in this thesis to investigate how grid integration of a 350 and a 1000 MW offshore wind farm will influence the grid frequency in the Norwegian hydro based power system. The power system model was more or less ready for use as it was delivered from Sintef, but some choices had to be made regarding the offshore wind farm and its connection to the onshore network. This chapter is used to explain how Sintef's model is set up and to justify the choices that has been made regarding wind turbine models, transmission technology etc.

### 6.1 DigSILENT PowerFactory

The computer program used to investigate how the offshore wind farms influences the onshore power system in the simulations in chapter 7 is the DigSILENT PowerFactory. The program will be referred to as PowerFactory in the following chapters.

PowerFactory is a computer tool for modelling of electrical systems and for analysing their static and dynamic behaviour. The program is in that respect suitable both for connecting an adapted internal wind turbine model to a pre-programmed power system model (see chapter 6.2) and for tuning and performing power balance and short circuit simulations.

An introduction on how to use the program is given in (Gleditsch, 2008).

### 6.2 Power system model of the Nordel synchronous system

To monitor the big picture of the inter-area power flow in Norway, Statnett's predecessor used among others a computer model of the Norwegian power system which contained lumped power generation at bus bars representing 8 geographical areas and inter-area tielines. The model was later tuned to illustrate the principles of secondary control in Norway (Bakken, 1997). To obtain a model which was simple enough to conduct this task, but also adequately detailed so that conclusions drawn from simulations performed with the model could be a basis for assessments of the realistic power system, several modifications were introduced, including:

- Construction of a system model consisting of both 300 kV and 420 kV bus bars consisting of one generator and one load each, and representing the geographical areas.
- The areas which were characterized by long geographical distances and a distinct division between generation in one part of the area and load in another were further divided into new areas.
- The lumped generation and load approximations were based on generation and consumption statistics for a peak load situation in Norway.
- The values of generation and load in each area were then adjusted to get a reasonably good correspondence with two different load situations: A typical peak load winter and a typical low load summer.

- The physical inter-area tielines were modelled in an aggregate way so that between any two areas only one tieline represents the full inter-area transmission capacity. For simplicity and due to lack of data, lines with voltage level from 132 kV and down were neglected.
- Based on frequency measurements from actual generation outages, the dynamic parameters of the generators in the peak load model were adjusted to give a response similar to the realistic power system to a casually chosen fault at heavy load; first the stationary droop of the turbine controllers were decided to approximate the stationary situation, then the generator inertias and the controller transient droops and time constants to approximate the transient responses.

The model has undergone changes, expansions and revisions since the 90s PhD work, most lately by K. Uhlen at Sintef Energy Research (Warland, 2008). The version that has been used to perform the simulations in this thesis is somewhat more comprehensive than the model described in this subchapter, and it was acquired from Sintef in October 2008 (Warland, 2008). The power system model described in this subchapter now imitates the Nordel synchronous system which comprises the areas accounted for in subchapter 5.1. The emphasis of the model, however, is on Norway and Sweden in general and Norway in particular. Finland is represented by two bus bars only and Eastern Denmark by one.

### 6.2.1 Conversion and alterations

A clarifying note to this paragraph: PSS/E is an abbreviation for Power System Simulator for Engineering. PSS/E is a computer tool developed by Siemens PTI which like PowerFactory is used to analyze electrical systems.

PSS is an abbreviation for Power System Stabilizer. It is used to add damping to the rotor oscillations of a synchronous machine by controlling its excitation (current). The PSS normally uses rotor speed deviation as an input signal. It's an addition to the excitation system which uses the generator voltage as input.

The model received from Sintef was a PSS/E model and thus had to be converted. Sintef's original PSS/E files didn't have to be altered for PowerFactory to read them, but an error in the PSSs was probably introduced in the conversion process; an internal signal in the PSSs wasn't inverted properly, an error which caused the PSSs to destabilize the system; small rotor oscillations were amplified until pole slip occurred in several synchronous machines and this consequently caused a system collapse. The error was corrected by copying the PSS model pss\_STAB2A from the PowerFactory library to the project folder and changing the inversion factor in the .dsl file manually from +1 to -1. dsl is an abbreviation for DIgSILENT Simulation Language.

The model could then be used more or less as it was handed over from Sintef, but a few objects were added, viz. double ups of a wind turbine model (ref. subchapter 6.3), wind farm side and grid side transformers and transmission cables in between the transformers.

### 6.2.2 Graphic file

The graphic representation of the Nordel synchronous system model that was established in (Gleditsch, 2008, p. 9&24) has been used as aid in the work with the PowerFactory models and simulations of this thesis.

### 6.2.3 Load flow solution

Prior to performance of the dynamic simulations of chapter 7, a starting point is needed, which means that a load flow solution must be established. A load flow solution was included in Sintef's model, but a new one that was calculated after the model had been altered has been used in that regard prior to the simulations.

### 6.2.4 Weaknesses

It has been argued and shown in (Bakken, pp. 61-66) that the Nordel synchronous system model is in satisfactory agreement with the factual system when it comes to load flow calculations and response to loss of generation. The same source does also declare that the model is ideal for illustration of the automatic secondary control principle in Nordel.

Some of the model characteristics do however make it unsuitable for other purposes of analysis. These characteristics are mainly associated with the size of the model; the extensive Nordel synchronous system which comprises thousands of bus bars and power system components has been compressed to a relatively small system consisting of tens of bus bars and lumped generators and loads. To that, the hydro power plants of the model have overall been set up with the same parameter values and this passes for the thermal power plants too. These parameter values are outlined in subchapter 6.4. As an example of the model's inadequacy, (Gleditsch, 2008) showed that it was practically impossible to determine differences in the ability to deliver balancing power from one hydro power plant to another.

The objectives of this thesis embrace somewhat similar issues as the ones of (Gleditsch, 2008) regarding balancing power, but by choosing to implement the LFC scheme in a centralized way on the bus bar representing Mid-Norway and dispersing the lumped Mid-Norway generation into smaller hydro power plants, fit out with real data (ref. subchapter 6.4), the former problems are trusted to be disregarded. Based on test simulations, the original Nordel synchronous system model is through the hereby and the subchapter 6.2.1 explained modifications considered to be qualified as a tool fit to solve the objective tasks of this thesis (ref. **Feil! Fant ikke referansebildet.**).

## 6.3 Wind farm model

In cases where the focus is on the collective impact of a large wind farm on a large power system, the wind farm can be represented by a single machine equivalent model for short term voltage stability analysis (Akhmatov, 2005, pp. 653-673). This is the case for this thesis, and the approach applies the following assumptions: The wind turbine model is represented with a scaled power capacity which equals the sum of the capacities in the wind farm, the actual power supplied by

the single machine equivalent is the sum of the power generated in the wind farm and the reactive power from the single machine equivalent is zero.

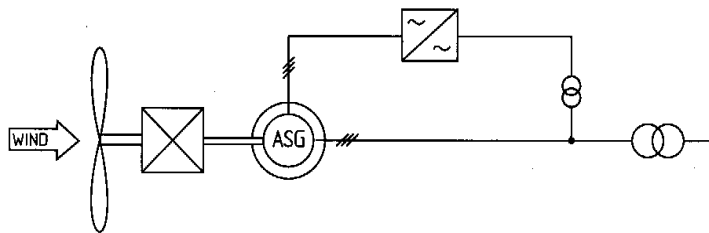
To set up the model, choices had to be made regarding connection point in the onshore grid, what kind of wind turbine model to use, what kind of wind data to use etc. Justifications for and information about these choices are given in this subchapter.

The wind farm in this thesis is consistently referred to as offshore. In reality, setting up a wind farm offshore involve some other technical challenges compared to onshore wind farms, regarding e.g. corrosion protection, erection, underwater cabling etc. In this thesis however, there isn't sought to find a solution to a specific offshore wind farm issue; as the paragraph above states the focus of this thesis is on a wind farms impact on an onshore power system. Calling the wind farm in this thesis offshore mainly owes to three circumstances:

- The power generation/wind data are taken from an offshore wind farm (ref. subchapter 6.3.5).
- The size; wind farms of this size aren't constructed onshore (ref. in subchapter 6.3.2).
- The fact that Norway's first offshore wind farm has been given concession in the area (ref. subchapter 2.2.4.3).

### 6.3.1 Choice of wind turbine concept

In the last years, the trend has moved from installation of a few wind turbines connected to the distribution system towards large transmission system connected wind farms with hundreds of MW of installed capacity. Owing to this trend and the fact that wind power is the fastest growing technology for renewable power generation in the world, focus has been drawn towards wind powers impact on power system operation. While single wind turbines in the beginning of the modern wind power era (the 1980's) were connected to distribution systems by applying rules of thumbs, large modern wind farms are required to comply with TSO grid codes and to contribute to power quality and power system stability (Tande, 2006).



**Figure 6 One-phase principle diagram of a DFIG.** Wind energy is driving the turbine blades which again are driving the main shaft. The rotational movement of the main shaft is converted to high-speed rotational movement in the gearbox, and the shaft's mechanical energy is converted to electric energy in the induction generator. The currents in the generator rotor windings are controlled by a voltage source power converter – allowing smooth operation in a wide range of speeds and in any power factor.

The grid connected wind farm in this thesis is modelled as two Doubly-Fed Induction Generators (DFIG). This is chosen since the DFIG wind turbine concept complies with the power quality and stability requirements mentioned above and since the concept is rapidly expanding and by now market dominating (Hansen & Hansen, 2007). Figure 6 shows a one-phase principle

diagram of the DFIG wind turbine configuration. As the name indicates the DFIG is based on an asynchronous (induction) generator. It has a multiphase wound rotor and a multiphase slipring assembly with brushes for rotor windings access. The stator windings are directly coupled to the constant frequency three-phase grid. So far the setup is similar to a normal induction generator. The DFIG departs from the regular setup by having its rotor windings coupled to the grid through sliprings and a bidirectional back-to-back Insulated-Gate Bipolar Transistor (IGBT) Voltage Source Converter (VSC). In short, this means that difference between electrical and mechanical frequency is levelled by feeding the rotor windings at variable frequency, allowing operation over a wide range of speeds. The generator can thus remain synchronised with the grid while the wind speed and accordingly the rotational speed of the rotor vary. The power converter is typically in the range of 25-30% of the generator rated power, allowing operation in the range of  $\pm 30\%$  of the synchronous speed. Such partially scaled power converters are cheaper than full-scale power converters and one of the reasons why the DFIG wind turbine concept is spreading.

Another great advantage of the DFIG wind turbine is that it can contribute to voltage control in the case of disturbances or a weak grid. This feature also owes to the power converter, which in fact is a pair of two converters; a rotor-side converter and a grid-side converter. By applying the converter to govern the rotor currents it's possible to control active and reactive power fed to the grid from the stator independently of the main shafts rotational speed. The DFIG may thus produce or absorb reactive power on the operator's instructions and is thereby able to contribute to grid voltage control. The power flow is controlled by adjusting the phase of the output current relative to the grid voltage. This feature is used in the simulations in chapter 7 where the wind farm is set to deliver active power only (the wind turbines are set to operate at unity power factor), since the scope of this thesis is to investigate the dynamics of the onshore power system. A drawback of the DFIG as a concept is the inevitable need for wear and tear sliprings.

The key source to this subchapter was (Hansen A. D., 2005, pp. 53-69).

### **6.3.2 Wind turbine model**

The PowerFactory library contains a DFIG wind turbine model which has been used to model the offshore wind farm connected to the Nordel synchronous system model. The wind turbine model was however modified in order to be able to vary its power generation in response to variable wind data, a feature missing in the original library model.

### **6.3.3 Size**

As reported in subchapter 2.2.4.3, the 350 MW offshore wind power project Havsul 1 has been given concession as the first offshore wind farm in Norway. In addition, the Havsul portfolio contains 650 MW which have been put on hold, since NVE wants to survey an offshore wind farms influence on the surroundings before handing out more licences.

Based on this, the generation capacity of the offshore wind farm connected to the grid in the simulations performed and presented in chapter 7 is set to 1000 MW. The wind farm is as explained in the intro to subchapter 6.3 modelled as two single machine equivalent wind turbines of 350 MW and 650 MW respectively. This is in accordance with (Akhmatov, 2005, pp. 653-673). Representing the offshore wind farm in this way opens for simulating both the situation as

of today with 350 MW offshore wind power (note well; as NVE has opened for, but not yet constructed) and a possible future scenario where a 1000 MW potential has been realized, with the wind turbine models operating at rated power.

Using the Havsul projects sizes as guidance for deciding on the offshore wind farms size is future-oriented also in a second sense (number one being that the project is closer to factual construction than any other Norwegian offshore wind farm project); the global trend seem to move towards larger wind farms, e.g. the 400 MW Anholt Offshore Wind Farm mentioned in subchapter 6.5 (Energinet.dk, 2009) and the 1000 MW London Array project southeast of England (Dong & E.ON, 2007).

### **6.3.4 Onshore connection point**

Subchapter 4.1 explained why Mid-Norway needs new generation capacity more than any other region of Norway, and subchapter 2.2.4 reported how the region has great coastal wind resources. The subchapters also reported how the region is the leading wind power region of Norway and that more wind power is likely to be commissioned in the region within the nearest future.

As a result of this, it has been chosen to connect the fictional offshore wind farm model in this thesis to the representation of Mid-Norway. As Mid-Norway is represented by one bus bar only, i.e. bus bar 6500 MID300 (henceforth shortened to busbar 6500), in the Nordel synchronous system model (ref. chapter 6.1) used in this thesis, the wind farm will be connected to that particular bus bar in the chapter 7 simulations. The bus bar's full name indicates the voltage level of the bus bar: 300 kV.

### **6.3.5 Power generation**

There is a strong correlation between wind speed and power generation in a wind turbine, see for instance Figure 3 in (Akhmatov, 2007, p. 62). The power generation in the offshore wind farm model differs between the simulation cases. In the FRT simulations of subchapters 7.1.2 and 7.2.2 the power generation in the offshore wind farm is initially set to maximum.

During the power fluctuations simulations of subchapter 7.1.1 and 7.2.1 real minute to minute wind data from the Danish offshore wind farm Horns Rev 1, kindly provided by the Swedish power company Vattenfall was used. Hub height wind speed measurements from offshore locations in Mid-Norway aren't found, but as subchapter 2.2.4.1 explains the area has stable and strong winds that are characterized by two dominating wind directions. The wind regime at Horns Rev is similar; strong average wind speed (roughly 10 m/s) and one dominating wind direction (DONG Energy, 2009). Hence, for day-to-day winds, it's been assumed that wind speed measurements from Horns Rev 1 can be used in Mid-Norway offshore wind farm investigations. The acquired wind data describe Horns Rev 1's wind speeds at the 31<sup>st</sup> of August 2003. That day, the winds were distinguished by rapid, excessive, repeating-character fluctuations, and they do therefore illustrate a more or less worst case scenario for a TSO regarding power planning, imposing maximum stress on both the primary and secondary control. The wind data are therefore suitable for the investigations of this thesis. The wind speed data have been put into the PowerFactory wind turbine model described in subchapter 6.3.2. A strict comparison between Figure 3 on page 11 and Figure 11 on page 41 shows that, when the starting time is factored in, the modelled power generation is in agreement with Horns Rev 1s factual

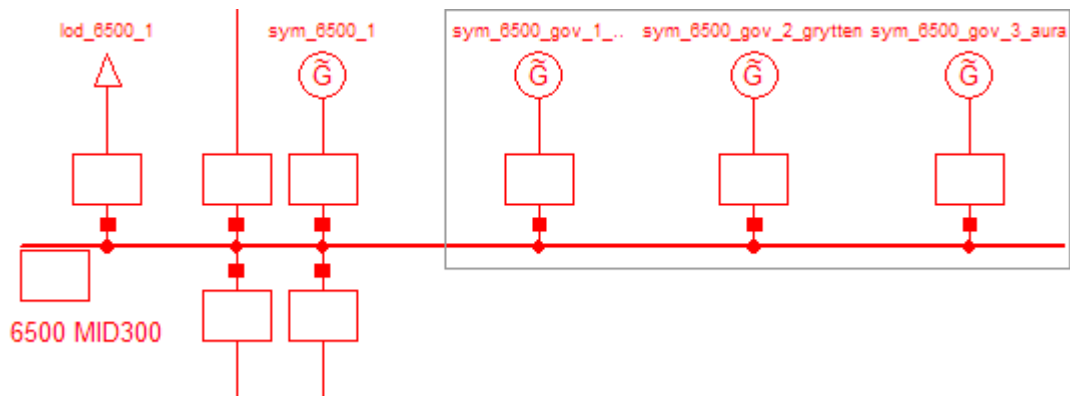
power generation of the date. The power fluctuations start after a couple of hours and data has therefore first been acquired after 108 minutes. The time was chosen since the power generation in the wind farm at that particular time was half of the available capacity.

In subchapter 7.1.3 forced shut-down of the offshore wind farm is simulated. In these simulations, the power generation has been fixed to maximum, viz. 350 MW and 1000 MW, at simulations starts, until a power generation descent begins at a determined ramp. This is implemented in the Nordel synchronous system model by feeding wind speeds in the wind turbine modes in agreement with the desired ramp. The ramp has been determined based on Horns Rev 1s forced shut-down time which is approximately 5 minutes (Kristoffersen, 2005). For simplicity and due to lack of data (no offshore wind farms of the simulated sizes is constructed to this date) a linear extrapolation of Horns Rev 1's ramp has been used to determine that the 350 MW will descend from maximum to zero generation in 11 minutes (equal to 31,8 MW/min). The upwards ramp gradient has been determined to half of the downwards (Power Rate Limitation principle), and restart of the offshore wind farm thus span 22 minutes (15.9 MW/min).

## 6.4 Hydro power plant models

The hydro power plants in the Nordel synchronous system model have not been altered. All are modelled as synchronous generators with Francis type hydro turbines, and they are shown as generator symbols in the PowerFactory graphics. All components' parameter values are as they were originally settled by Sintef. When disregarding minor differences, this means that permanent and temporary droop, turbine gain, filter and governor time constants etc. are the same for all of the hydro power plants of the power system model; this is a weakness, as described in subchapter 6.2.4. The hydro power plants are modelled without surge chamber effects or penstock dynamics. Typical parameter values of the hydro power plant governors are included in Appendix 12.4, and additional information about the different component models of the hydro power plants can be found in (Gleditsch, 2008, p. 14&25).

The hydro power plant connected to bus bar 6500 is an exception. The bus bar represents Mid-Norway in the Nordel synchronous system model and is originally set up with one generator and one load. The whole power generation capacity in the region is merged and represented by this lumped generator. For analysis purposes that are described in subchapter 6.7, three new hydro power plant models have been assigned to bus bar 6500 in addition to the original lumped generator. The three new hydro power plant models have been given the generation capacities of three of Statkraft's hydro power plants. These generation capacities are shown in Table 3 on page 38. The generation capacity of the bus bars' original lumped hydro power plant is reduced in accordance with the sizes of the three new hydro power plants. The new hydro power plants have been set-up with the same parameter values as the original hydro power plant connected to bus bar 6500. Figure 7 shows the components of bus bar 6500.



**Figure 7** Segment of bus bar 6500 from the Power Factory graphics (ref. subchapter 6.2.2) showing the components that are connected to the bus bar. This includes the three new hydro power plant models in the grey squared box to the left, one load and the original lumped generator. The three new hydro power plants have been separated from the lumped hydro power plant by reducing the lumped hydro power plants generation capacity in correspondence with the new hydro power plants generation capacity. An explanation on why this is done is given in subchapter 6.7. The parameter values of the lumped and the new hydro power plants are the same. The figure also indicate the transmission lines to the adjacent bus bars, viz. 6700 NOR300, 5100 EAST300 and 3244 SV-M2. The figure is trimmed to fit the page; the two single machine wind turbine equivalent models are in the graphic model in PowerFactory connected to the right of the rightmost hydro power plant of the bus bar.

## 6.5 Transmission

Power can be transmitted as either alternating current (AC) or direct current (DC). As power losses are reduced with increasing voltage levels, there are two real possibilities for transmission of power from an offshore wind farm to the onshore power system, i.e. HVAC or HVDC transmission (the notation High Voltage (HV) is used for voltage levels higher than 1000 V).

Underwater cables are a prerequisite for power transmission from offshore wind farms to the onshore grid, while power onshore normally is transmitted through overhead lines. Overhead lines differ from underwater cables with respect to their construction, and a major distinction is that the susceptance is much higher per unit of length in cables than in overhead lines. This is mainly because the conductors are closer to each other and surrounded by metallic screens in cables. Susceptance is the imaginary part of admittance, or in other words an indication of with which ease AC passes through a capacitance or an inductance. An effect of this is HVAC's ineptness in power transmission through long cables: When the cable exceeds a certain length, the total cable susceptance will become so large that the cable will transmit no active power and solely produce reactive power due to current-voltage phase displacement. An AC cable's useful range can however be extended by compensating for reactive power in the cable's ends.

HVDC transmission is principally based on two converter stations with a cable in between; AC is rectified in the converter station in one end of the cable and transmitted through the cable as DC before being inverted in the second converter station. The modern sophisticated HVDC technologies like HVDC Light and HVDC Plus use transistors in the switching process (older versions used thyristors). Unlike thyristors, transistors have turn off leading capability, allowing full control of the AC output amplitude and phase angle. A direct consequence of this is that the



converters can control active and reactive power independently, and reactive power will in other words neither be produced nor consumed (unless desired) in the case of modern technology HVDC transmission. This quality, together with the converters ability to protect wind turbines against grid faults, is a major modern HVDC contra HVAC advantage.

Choosing the right transmission technology can be a challenge. HVDC has some technological advantages compared to HVAC, but HVAC is cheaper; at a certain transmission distance, HVDC technology shall be used in order to prevent problems related to reactive power production in the cable. Up to that critical distance, which is among others dependent on voltage level and reactive power compensation, HVAC is arguably the best alternative. All in all, there seems to be a consensus on the cost intersection distance of 50 km between specialists (de Alegria, et al., 2008); HVAC systems are estimated to be the most cost effective alternative for the shorter distances, while HVDC transmission is cost competitive for the exceeding. Semiconductor cost reduction and more stringent grid connection regulations may make HVDC technologies cost competitive on even shorter distanced in the future.

The Danish Energy Agency has launched a tender for the new 400 MW Anholt Offshore Wind Farm. The project is to be commissioned by 2012 and is located approximately 25 km off the chosen connection point on Jutland. The Danish TSO will be responsible for establishment of the technical installations for carrying the power from the wind farm ashore. As this is written, a solution with two (for increased reliability) cables carrying 220 kV AC seems to be the preferred one (Energinet.dk, 2009). Given the water depths of Mid-Norway and under the presumption that construction of an offshore wind farm in the immediate future must use a solution with seabed-founded wind turbines, a transmission solution similar to the one chosen for the Anholt project seems reasonable.

Both common economical assessments and up to date practice support HVAC transmission at any plausible distance-to-shore for a Mid-Norway offshore wind farm. A solution with two 220 kV AC cables has thus been chosen to carry the power ashore from the offshore wind farm in the simulations of chapter 7.

This subchapter is mainly based on (Mohan, et al., 2003, pp. 596-640) and (Sommerfelt, 2007).

## 6.6 Power plan

A power plan is used in the generic LFC model shown in Figure 8 on page 36 to determine the ACE, which is thereafter used as control signal in the PI controller of the LFC (ref. subchapter 5.2.2). The power plan used in the simulations in this thesis is however not drawn up like in the Nordel synchronous system (ref. subchapter 5.2.1); the power plan in this thesis is constant, i.e. neither the total consumption nor the total generation changes. The total consumption equals the static loads connected to the bus bars in the Nordel synchronous system model.

Keeping the power plan constant is an assumption that has been chosen mainly due to lack of data. In order not to diminish the value of the results, the power fluctuations simulations of subchapter 7.1.1 and 7.2.1 have been divided into several two-hour periods. This is done because it can be argued that keeping the power plan constant for a two-hour period is reasonable, and such a discussion was presented in (Gleditsch, 2008, pp. 15-16). The FRT and forced shut-down

simulations of chapter 7 are not affected by the power plan due to the relatively short durations of such events.

A constant power plan does also involve a positive effect; the power generation signals in the three hydro power plants contributing to the LFC are isolated, making it easier to analyze the LFC's suitability as secondary control mean in the Nordel synchronous system; a variable power plan would have added an extra dimension to the simulations, rendering it difficult to determine if power curve swings owed to the LFC or the power plan.

Nevertheless, a constant power plan must be regarded as best-case circumstances for the player responsible for maintenance of power balance, and hence it must be assumed that the swings of the frequency and power result curves of the power fluctuations simulations in chapter 7 are smaller than the factual swings in the Nordel synchronous system (this comparison is based on the assumption that the model is a 100% correct representation of the factual system).

## 6.7 Implementation of the LFC scheme

Subchapter 5.2 explains from a theoretical point of view how LFC is used as secondary control in among others the UCTE. This subchapter will explain how LFC is practically implemented in PowerFactory in the Nordel synchronous system model of chapter 6. The centralized LFC structure is chosen (ref. subchapter 5.2.2), which means that the secondary control is performed by a single centrally located controller of one control area (corresponding to one bus bar (6500) in the Nordel synchronous system model).

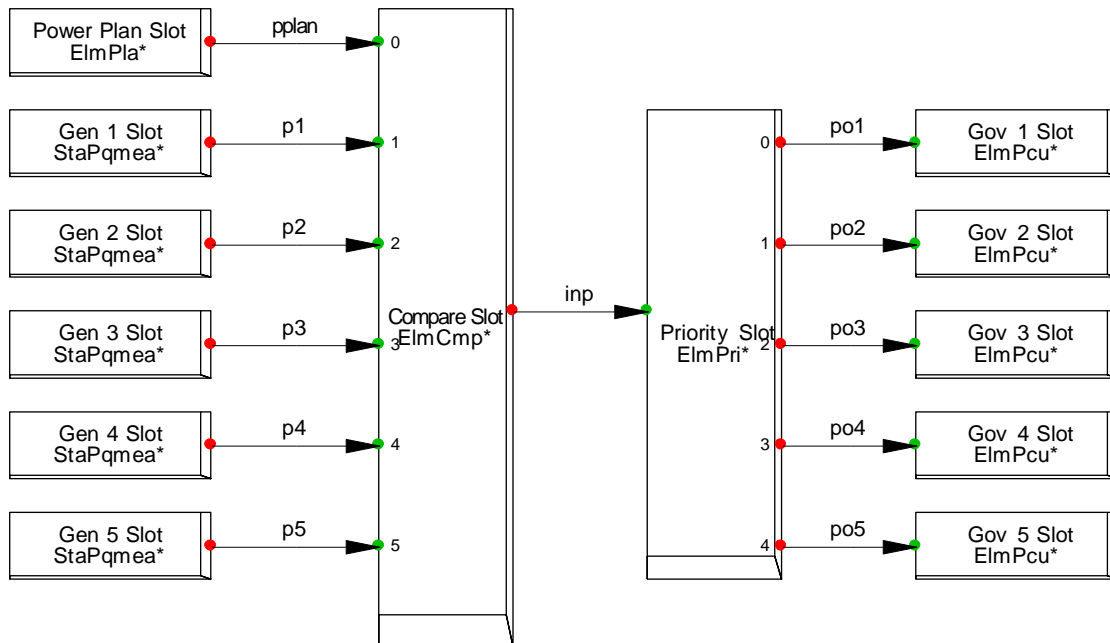
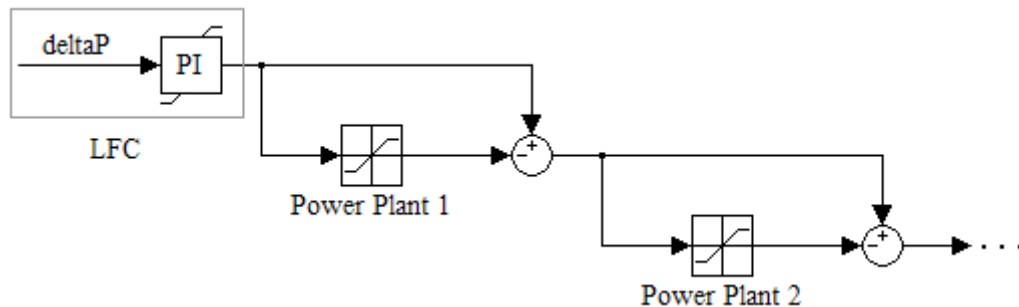


Figure 8 Generic LFC model as it is implemented in PowerFactory. The leftmost slots represent from top to bottom: the power generation plan, total generation in the offshore wind farm models and generation in the four hydro power plants connected to bus bar 6500. The power deviation is calculated and processed through a PI controller in the compare slot, and the regulating power demand signal is subsequently passed on to the

governors of the power plants that provide regulating power in accordance with the priority structure that is shown in Figure 9.

Figure 8 shows how the secondary control in the Nordel synchronous system model has been implemented as LFC in PowerFactory. The slots to the left represent from top to bottom: The power generation plan, the total generation in the offshore wind farm models, generation in the lumped hydro power plant and generation in the three hydro power plants that are appointed to constitute the LFC reserves. As described in subchapter 6.4 these hydro power plants are located on bus bar 6500. The implemented LFC departs from the classic setup shown in Figure 4 by only using the ACE as control signal in determining how much balancing power is needed; the frequency deviation which is a part of Figure 4 isn't used.



**Figure 9** Principle sketch of the priority key that is implemented in PowerFactory. The structure ensures that the hydro power plants designated to deliver regulating power conduct their tasks in accordance with their response times. The left framed box corresponds to the left row of slots and the Compare Slot of Figure 8. The leftmost plants have the fastest response times. As this structure is implemented in PowerFactory, the power plants are represented by time delay blocks on the form  $1/(1 + sT)$  with the time constants equal to the response times presented in Table 3. The signals that are going out of the priority slot in Figure 8 and are used as control signals in the power plants' turbine governors can also be recognized in this figure; they are fetched from behind the power plants, i.e. between a power plant and the summation point to the right of it.

How a LFC priority key has been implemented in PowerFactory is shown in Figure 9. A general comprehension of the LFC will most easily be obtained by collating Figure 8 with Figure 9. The total power generation in all the system's power plants is compared to the power plan in the Compare Slot in Figure 8. Figure 9 indicates how the ACE is eliminated; the power imbalance signal is processed through the PI controller of the LFC and balancing power is generated in proportion to the size of the ACE and in accordance with the generation characteristics of the hydro power plants. The mechanism is executed pursuant to the desired priority sequence, which in this thesis is organized after the hydro power plants response times. The leftmost (fastest, i.e. Aura) hydro power plant acts first, starting to generate the maximum amount of power it's capable of. The instantaneous remainder of the ACE is then used as control signal in the next (second fastest, i.e. Grytten) hydro power plant which in the configuration of Figure 9 is located to the right of the first acting power plant. The routine continues until power balance is re-established. In the power fluctuations simulations of this thesis, the anticipated demand is constant, and so the scheduled power generation, and with that the power plan, is constant, as described in subchapter 6.6. In practice, this means that the three designated hydro power plants that make the LFC reserves will balance the offshore wind farms power generation only; the

calculated ACE and the PI controller make sure the offshore wind farm and the four power plants together generate an amount of power equal to the anticipated power generation in the offshore wind farm. The PI controller is of standard type; see for instance (Balchen, et al., 2004, ss. 332-335), and the integrator time constant  $T_{int}$  is set to 100 seconds and the proportional gain  $K_p$  to 0.5 pu. These values have been chosen after the UCTE recommendations presented in subchapter 5.2.2. The initial PI controller limits correspond to the maximum power generation in the offshore wind farm; for the 350 MW case the upper and lower boundaries are  $\pm 175$  MW and for the 1000 MW case the limits on the 650 MW machine are determined accordingly. Simulations were also conducted with other limits.

The LFC priority structure of this thesis constitutes four levels in total; the first two mentioned in the above paragraph, the third being the third fastest hydro power plant Jostedal, and the last being the slow acting lumped hydro power plant. This ensures proper performance of the centralized LFC control principle; the slow acting reserves (the lumped hydro power plant) ultimately take over for the fast acting reserves (Aura, Grytten and Jostedal), allowing them to decrease generation and thus rendering them able to react to coming disturbances. This structure fits the primary and secondary controls duty assignments according to subchapter 5.2.

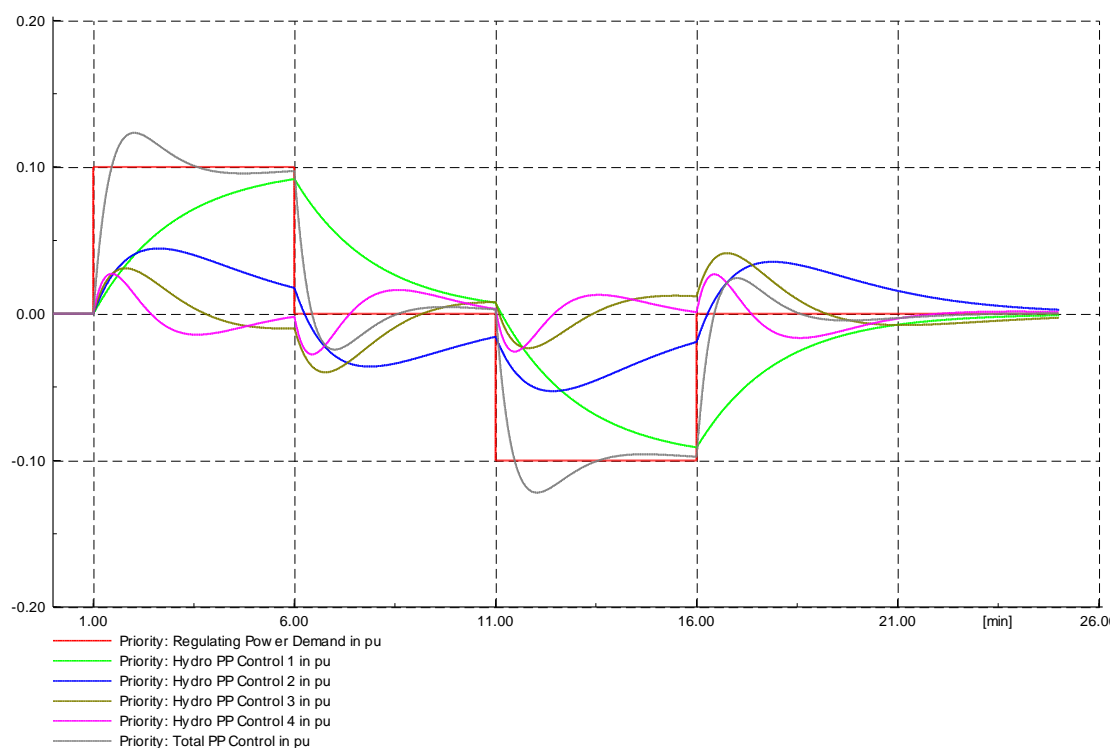
Hydro power plant	Max generation [MW]	Start generation [MW]	Response time [s]
Aura	234	175	40
Grytten	143	118	60
Jostedal	288	217	80
Lumped plant	1200	1000	120

**Table 3 Maximum power generation capacity, initial generation and implemented time constant response times of the four hydro power plant models that are connected to bus 6500 in the Nordel synchronous system model. The maximum power output of the three uppermost hydro power plants have been acquired from Statkraft's web page (Statkraft, 2009), while the generation capacity of the lumped hydro power plant has been calculated by subtracting the capacities of the three real hydro power plants from Mid-Norway's original capacity. The response times are fictitious; they are calculated based on real hours for upward regulation of power in the three hydro power plants, but do not represent any physical quality of the plants. The response time for the lumped hydro power plant has been determined in accordance with the want of a slower response than for the three real plants.**

Table 3 shows the maximum power output and the response time of the four hydro power plants connected to bus 6500. The power output values are publicly available through Statkraft's web page (Statkraft, 2009), while the response times of Aura, Grytten and Jostedal have been derived from the real response times of the hydro power plants, kindly given by Statkraft's system control centre in Gaupne which governs their Mid-Norway power plants (Lind, 2009). Jostedal, one of the hydro power plants Statkraft has provided information about is in fact not part of the Mid-Norway electrical area as it's been defined in subchapter 2.2.4, but it's nevertheless been chosen to engage it at the Mid-Norway bus bar as shown in Figure 7. This is chosen because the configuration in that way fulfils the centralized LFC requirements and because experience from (Gleditsch, 2008) showed that connecting the hydro power plant to its correct bus bar which is located close would not bring noticeable differences on the simulations.

The response times have been determined by measuring the time from setpoints have been given by the system control centre till the machines generate the new set power value. The 63% time constant routine has then been applied on the measured time values, pursuant to normal

time constant ( $\tau$ ) determination, see for instance (Balchen, et al., 2004, ss. 43-44). In other words,  $\tau$  represents the time it takes from a new setpoint is given till approximately 63% of the new reference value is reached. The machines have in all cases given from Statkraft been regulated upwards from relatively low productions. For those hydro power plants that consist of multiple machines, one machine only has been used in the time determinations. Experience showed that the time from a setpoint was given till the machine generated the new power value was not entirely consistent, and the so-called response times of this thesis have thus been rounded off to the values shown in Table 3. They are nonetheless still in the correct range compared to the time measurements from Statkraft. The intention behind introduction of the response times was in any case not to get a totally correct representation of the real power system; the intention was to find a way to distinguish between the model's different hydro power plants' abilities to contribute to solution of the LFC problem. Introduction of the response times in the LFC priority key makes this possible, and one core issue that was run into in the simulations in (Gleditsch, 2008) is thus bypassed.



**Figure 10** Step response test of the four hydro power plants connected to bus bar 6500. The composite LFC model was disconnected during the test in order to ensure that all four hydro power plants start to contribute initially and contemporary. The red signal shows the regulating power demand and the grey the sum of the power generation signals (ref. Figure 9 on page 37); made up of the contributions from the hydro power plants, viz. Aura, Grytten, Jostedal and the lumped generation (pink, brown, blue and green curves respectively). The y-axis scale is measured in pu referred to the maximum generation capacity.

The results of a step response test of the LFC scheme is shown in Figure 10. The figure shows that the LFC responds rapidly with the chosen PI controller parameter values; power generation corresponding to the new demand is met after approximately 40 seconds. The cost of a rapid response is an expected overshoot, a dilemma owing to the PI controller characteristics. The simulation results of in subchapter 7 show that the PI controller properties and with them the

overshoot don't jeopardize the controllability or stability of the system. The test also showed that the priority key works as intended; the lumped hydro power plant adjusts its power generation setpoint slowly, rendering temporary power generation cuts in the fast responding hydro power plants possible so they can be able to act to coming disturbances. Their generations are reduced as the deviation from the power plan decreases.

It shall be noticed that by tailoring the time delay blocks, the priority key used in this thesis could easily be altered to fit other criteria, for instance economic dispatch with respect to lowest production cost or lowest start-up cost, ratio of storage filling, etc.

## 7 Simulation results

This chapter shows results from power fluctuations, fault ride through and forced shut-down simulations performed in PowerFactory with the Nordel synchronous system model presented in chapter 6. It's been attempted to limit the number of results shown in the report; hence only simulation results that are believed to contribute directly to increased understanding of the questions arisen in the objectives of the thesis (ref. the Preface) either as principal explanations or by means of the results they display, have been included. Some figures have been cropped in order to arrange for a neat layout.

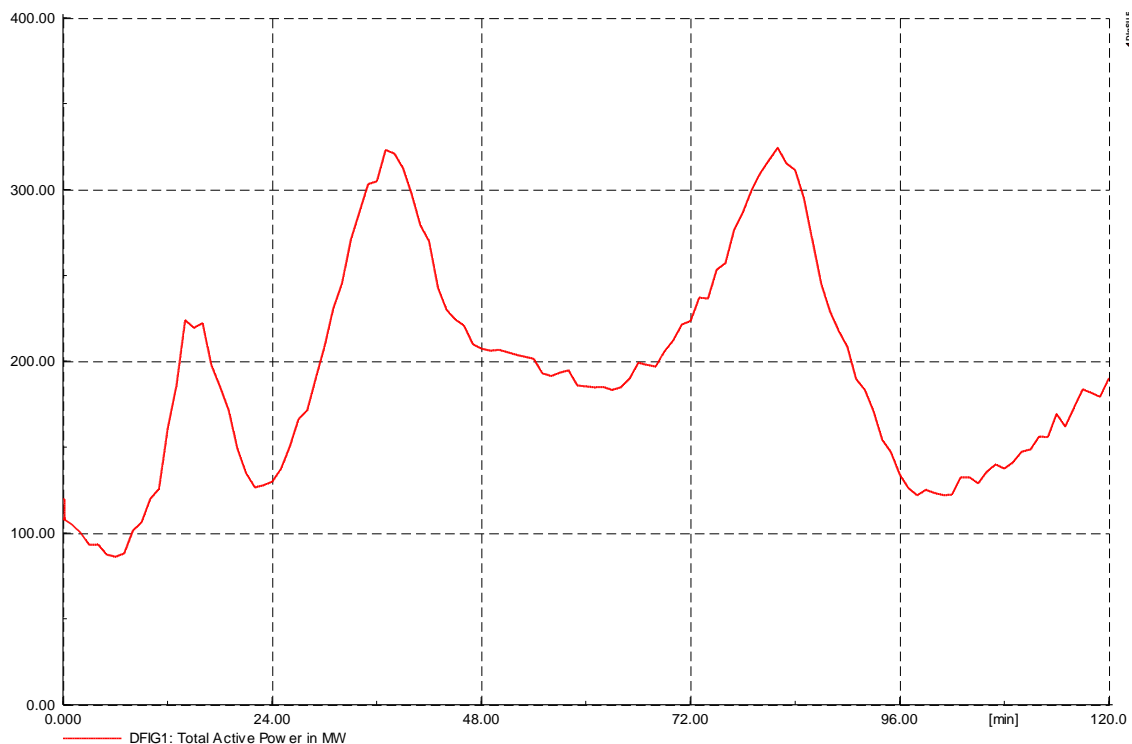
This chapter displays graphic results with the explanations needed to comprehend them only; all discussions on the graphic results are placed in chapter 1.

### 7.1 Stage 1: 350 MW

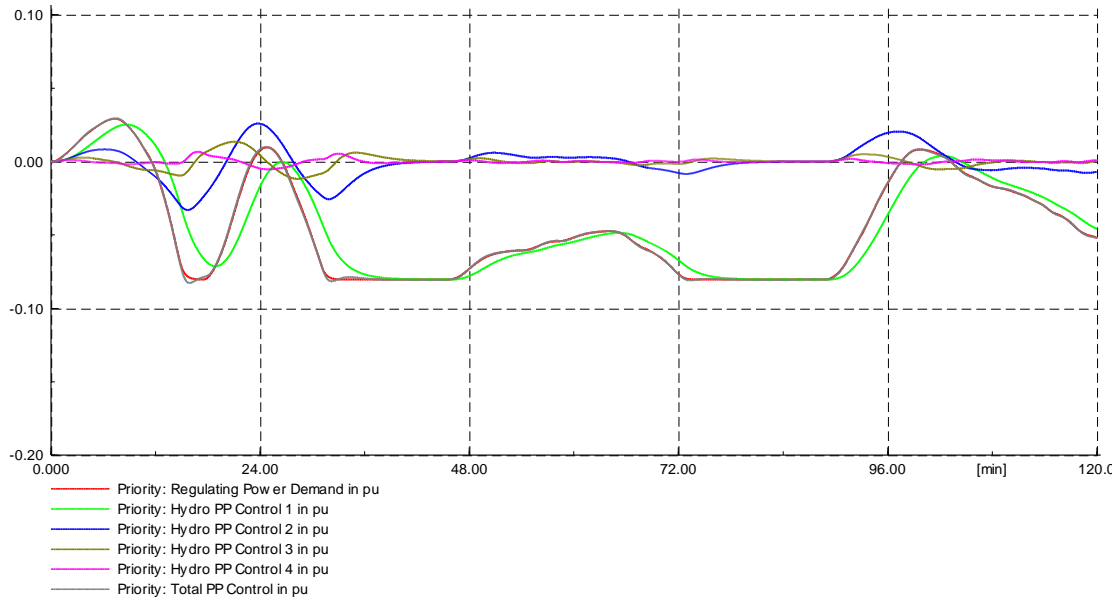
In this stage the 650 MW offshore wind farm model was set as out of service in PowerFactory.

#### 7.1.1 Power fluctuations

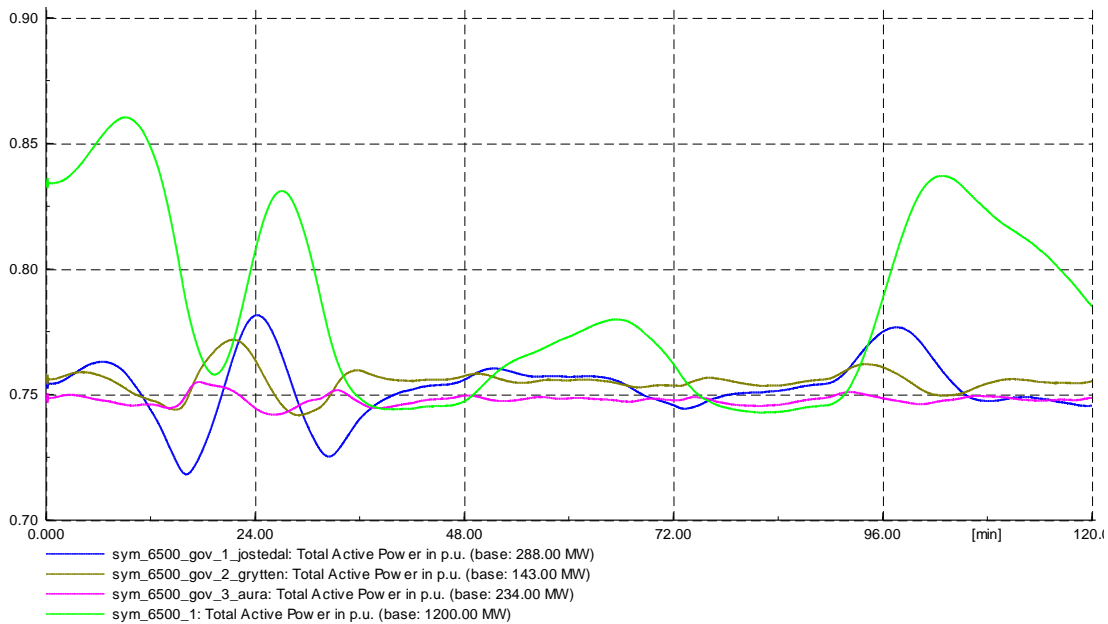
The time frame of these simulations is hours. The time segment from the hours 10-12 is displayed as these hours covered the most severe power generation fluctuations in the offshore wind farm. The LFC boundaries were determined to  $\pm 175$  MW as explained in subchapter 6.7.



**Figure 11 Active power generation in the offshore wind farm during the hours 10-12. The power generation in the PowerFactory model is based on the wind data from Figure 3 on page 11. Y-axis values are in MW.**

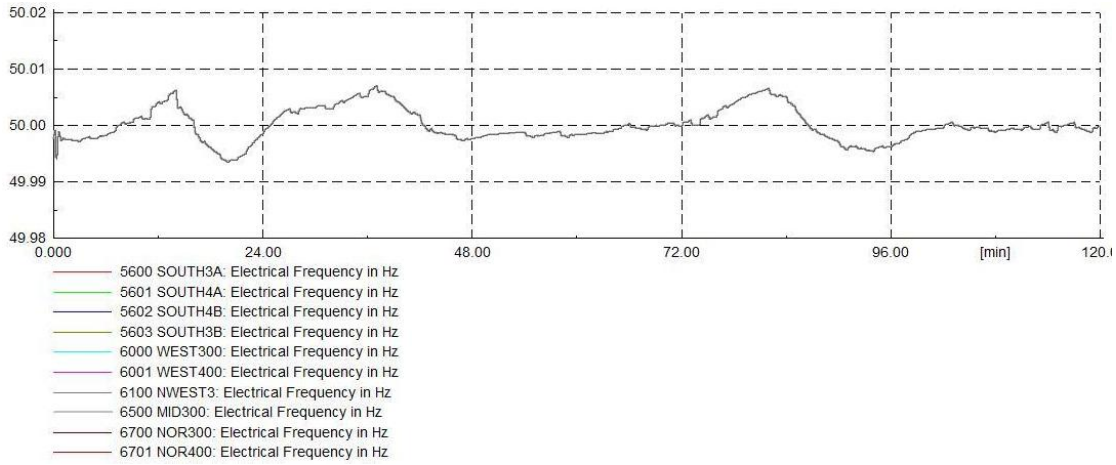


**Figure 12** Regulating power demand signals sent to the hydro power plants connected to bus 6500 from the LFC during the hours 10-12 (ref. Figure 9 on page 37). The red curve represents the total demand and the brown curve the total contribution from all four hydro power plants connected to bus bar 6500. The individual control signals for the hydro power plants Aura, Grytten, Jostedal and the lumped generation are pink, brown, blue and green respectively. The y-axis values are measured in pu referred to the installed generation capacities (ref. Table 3 on page 38).



**Figure 13** Active power generation in the hydro power plants connected to bus bar 6500 during the hours 10-12. The pink, brown, blue and green curves represent the hydro power plants Aura, Grytten, Jostedal and the lumped generation respectively. While Figure 12 showed the regulating power demand signals, these curves show the factual power generation (determined on the basis of the power demand signals). The y-axis scale is measured in pu referred to the maximum generation capacity bases that are shown below the figure.

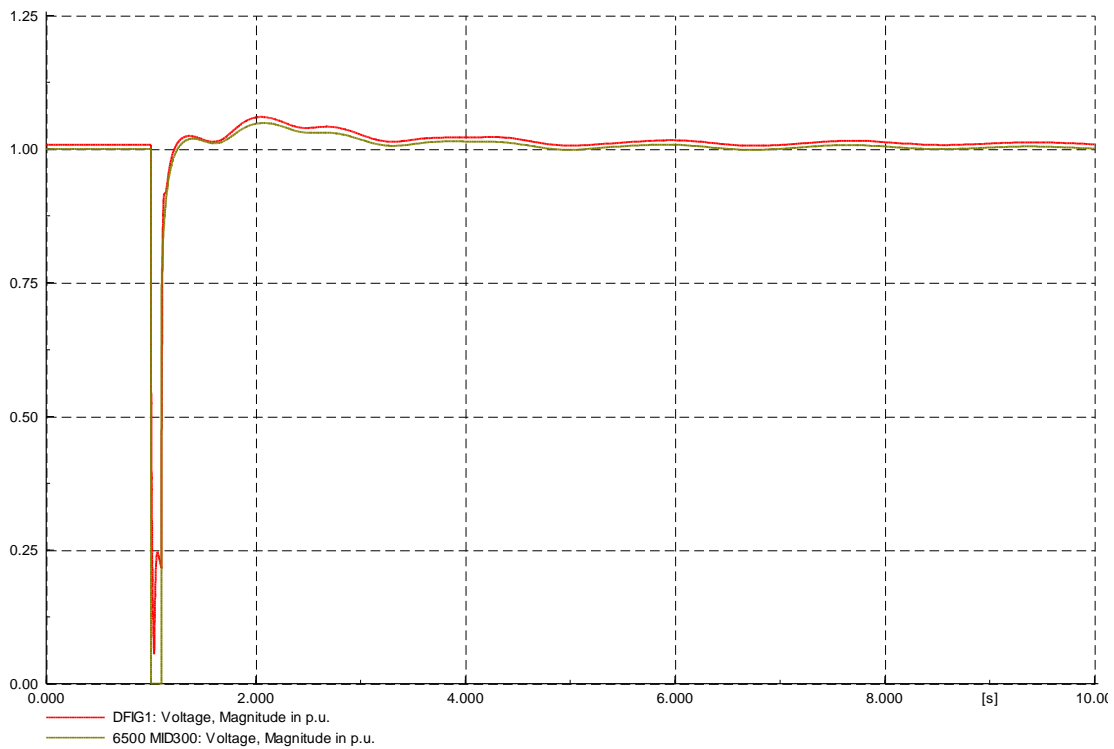




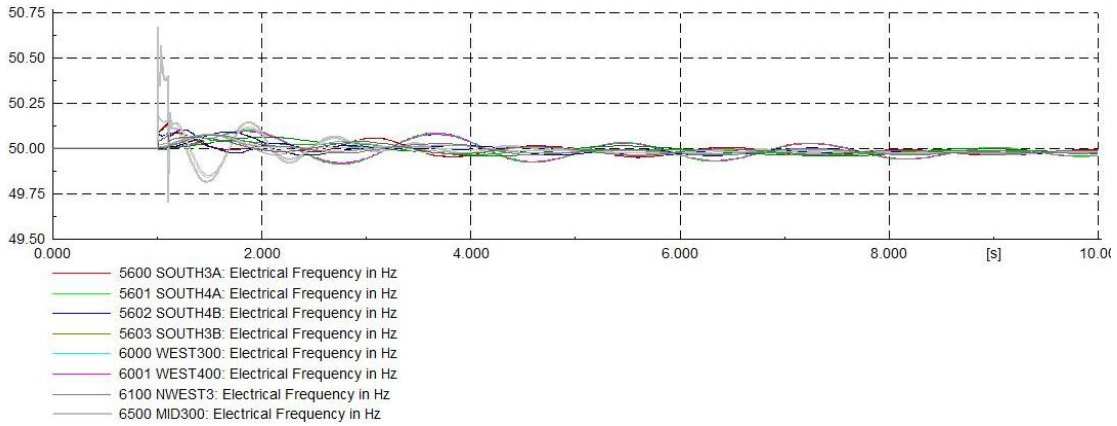
**Figure 14** Electrical frequencies of the bus bars in the Nordel synchronous system model during the hours 10-12. The list of buses has been cropped; the frequencies of all the bus bars in the power system model are plotted in the graph, but the curves are congruent since all the buses are part of the same synchronous system. The y-axis values are measured in Hz.

### 7.1.2 Fault ride through

FRT simulations were performed by introducing 0.1 second lasting 3-phase short circuit faults on selected bus bars. The time frame of these simulations is seconds.



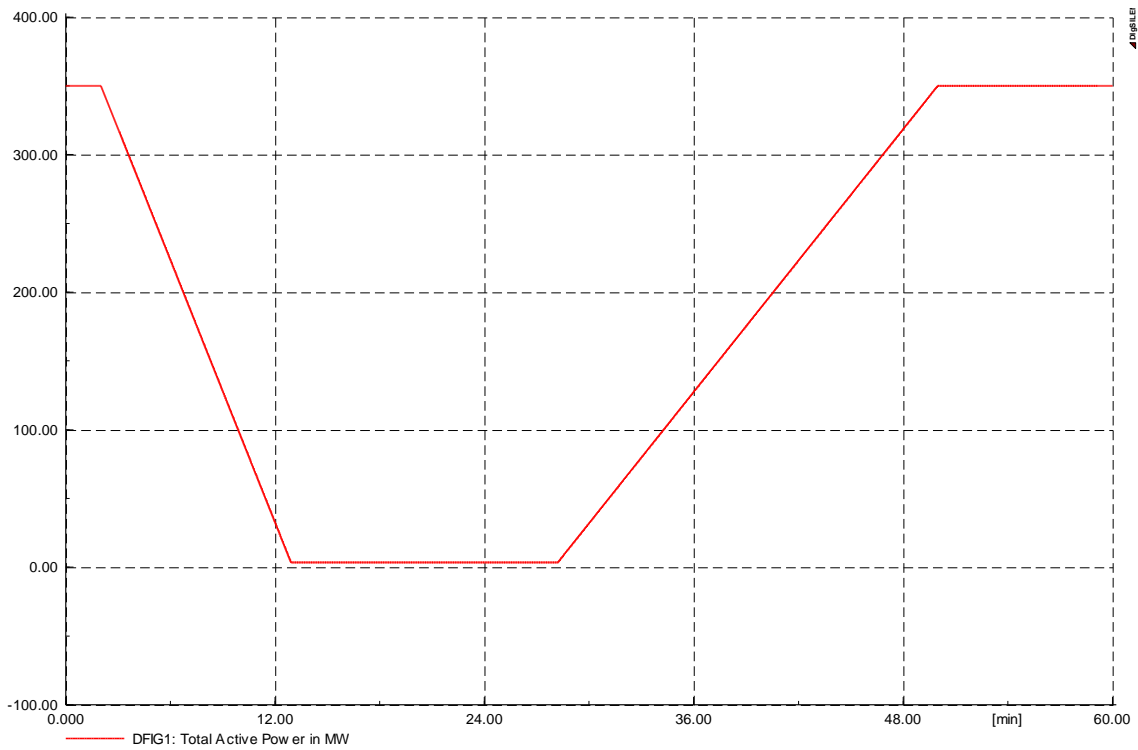
**Figure 15** Offshore wind turbine model (red) and bus bar 6500 (brown) voltage curves during a 3-phase, 0.1 seconds lasting short circuit at bus bar 6500, The y-axis values are measured in pu.



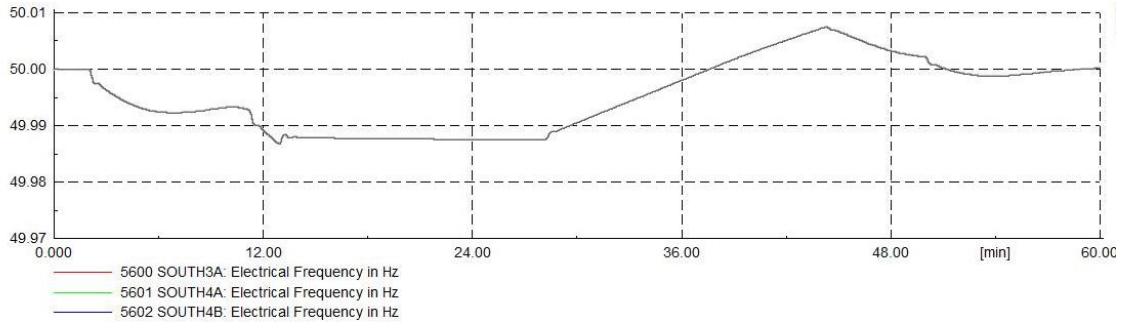
**Figure 16** Electrical system frequencies of the bus bars in the Nordel synchronous system model during a 3-phase, 0.1 second lasting short circuit fault at bus bar 6500. The grey curve which undergoes the greatest fluctuations shows the electrical frequency at bus bar 6500. The list of buses has been cropped, ref. caption under Figure 14 on page 43. The y-axis values are measured in Hz.

### 7.1.3 Forced shut-down

Forced shut-down simulations have been conducted with the ramps described in subchapter 6.3.5, viz. 31.8 MW/min downwards and 15.9 MW/min upwards at subsequent restart. The time frame of these simulations is minutes.



**Figure 17** The red curve shows the active power generation in the offshore wind farm equivalent model during forced shut-down and subsequent restart. The y-axis values are measured in MW.



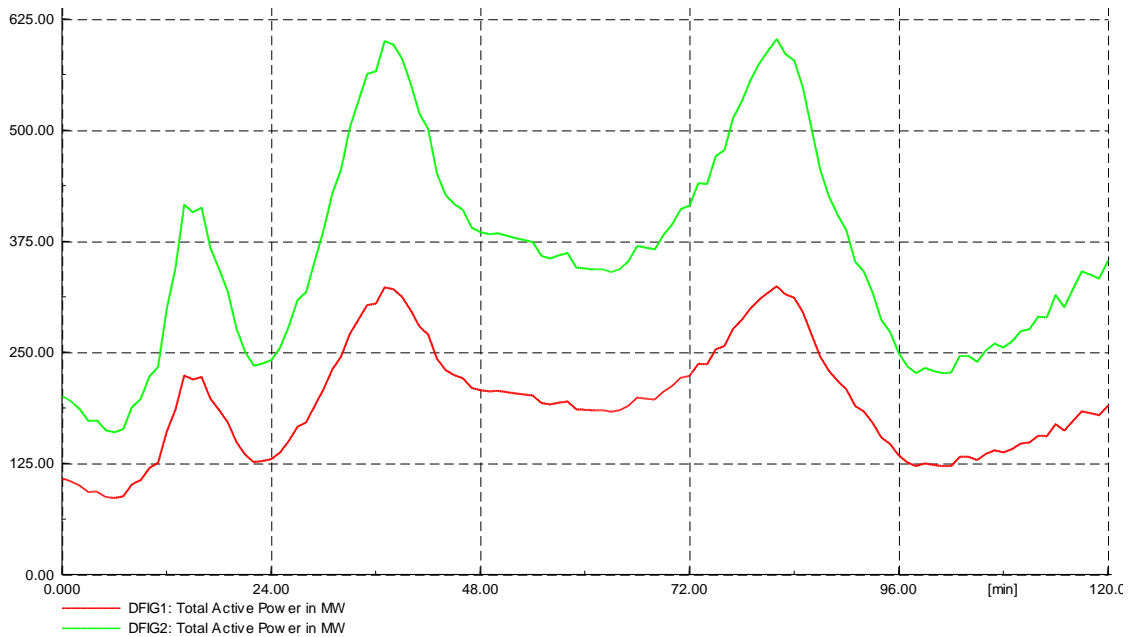
**Figure 18** Electrical system frequencies of the bus bars in the Nordel synchronous system model during forced shut-down and subsequent restart of the 350 MW offshore wind farm model with  $\pm 350$  MW LFC boundaries. The list of bus bars has been cropped, ref. Figure 14’s caption on page 43. The y-axis values are measured in Hz.

## 7.2 Stage 2: 1000 MW

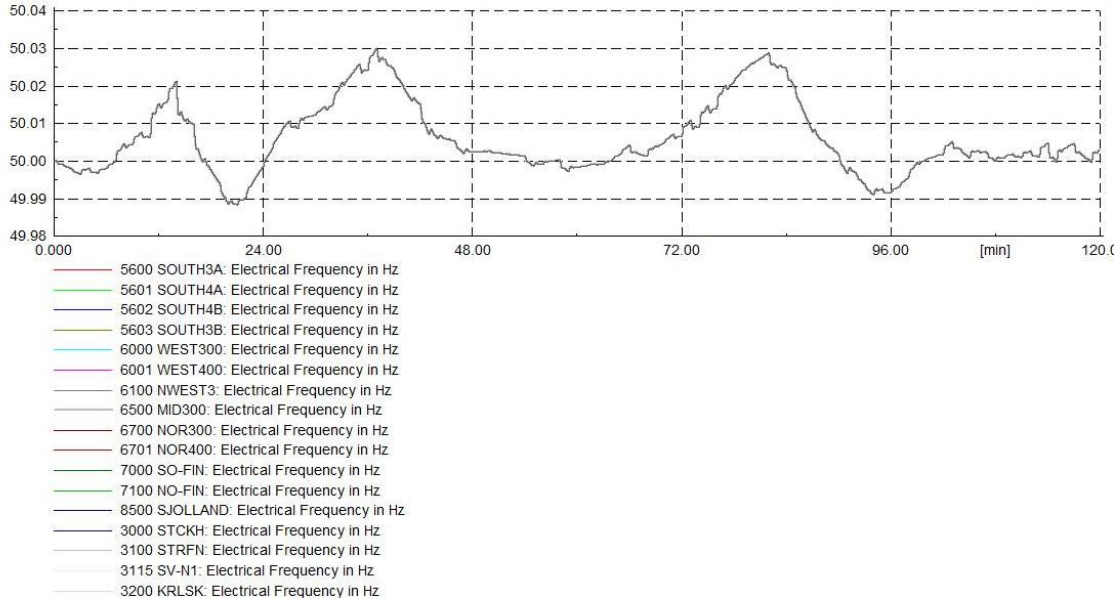
In this stage of the simulations the second offshore wind farm model is put in service so that a total generation capacity of  $350 + 650 = 1000$  MW is realized.

### 7.2.1 Power fluctuations

The time frame of these simulations is hours. The time segment from the hours 10-12 is displayed as these hours covered the most severe power generation fluctuations in the offshore wind farm, and simulations were only run for these hours. The LFC boundaries were initially  $\pm 350$  MW.

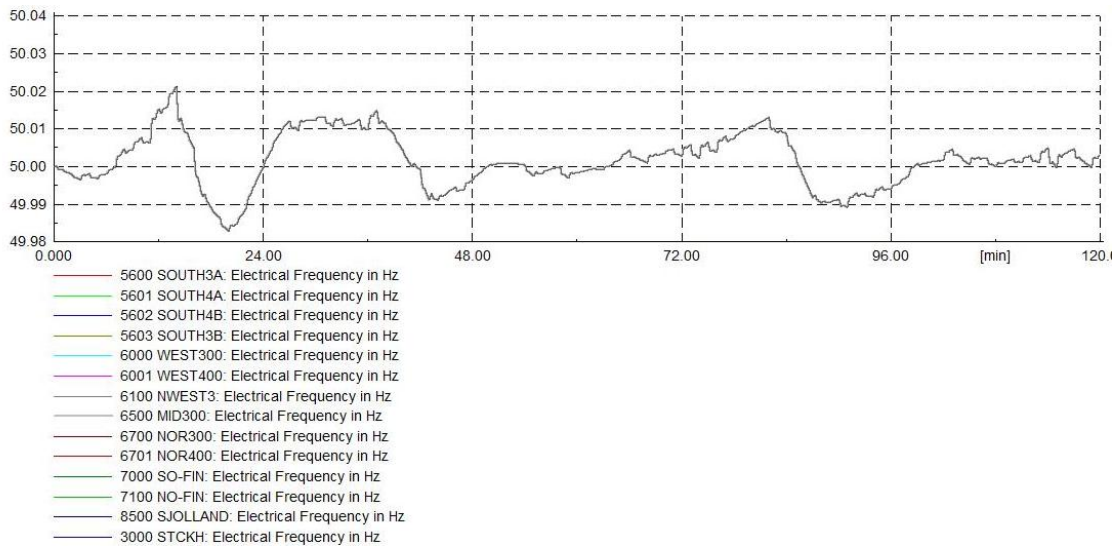


**Figure 19** Active power generation in the 350 MW (red) and the 650 MW (green) offshore wind farm models during the hours 10-12. The y-axis values are measured in MW.



**Figure 20** Electrical frequencies of the bus bars in the Nordel synchronous system model during the hours 10-12. The list of bus bars has been cropped; the frequencies of all the bus bars in the power system model are plotted in the graph, but the curves are congruent since all the buses are part of the same synchronous system. The y-axis values are measured in Hz. The LFC boundaries are  $\pm 350$  MW.

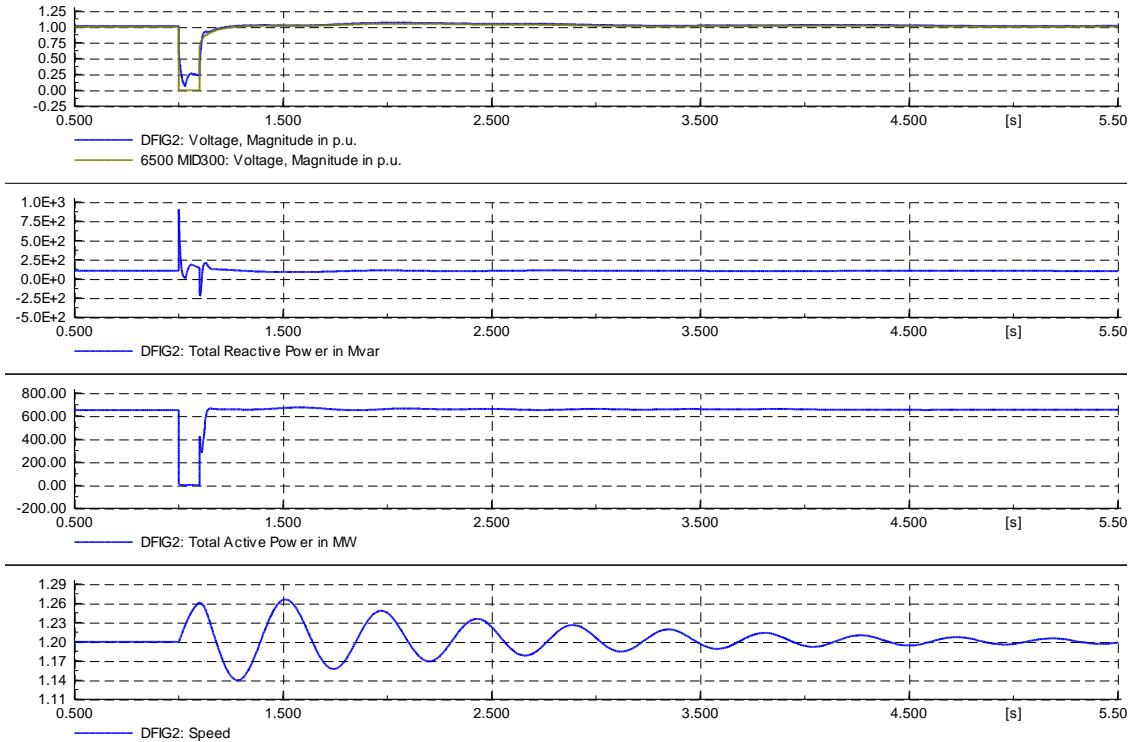
Figure 21 shows the Nordel synchronous system model frequency with 1000 MW offshore wind power in operation and with the lower boundary expanded to -650 MW in the LFC control scheme. The upper boundary is still +350 MW.



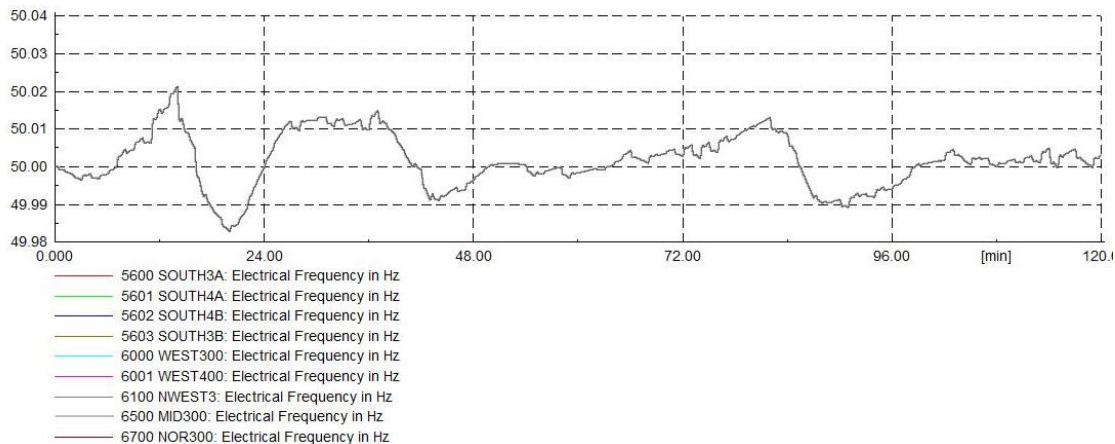
**Figure 21** Electrical frequencies of the bus bars in the Nordel synchronous system model during the hours 10-12. The list of buses has been cropped; the frequencies of all the bus bars in the power system model are plotted in the graph, but the curves are congruent since all the buses are part of the same synchronous system. The y-axis values are measured in Hz. The LFC boundaries are +350 MW and -650 MW.

### 7.2.2 Fault ride through

FRT simulations were performed by introducing 0.1 second lasting 3-phase short circuit faults on selected bus bars. The time frame of these simulations is seconds.



**Figure 22** The curves show, during a 3-phase, 0.1 second lasting short circuit fault at bus bar 6500, from top to bottom: Voltage, reactive power generation, active power generation and speed in the 650 MW offshore wind farm equivalent model. The descriptions are small, so please turn towards the FRT figures in subchapter 7.1.2 for larger type sizes.



**Figure 23** Electrical system frequencies of the bus bars in the Nordel synchronous system model during a 3-phase, 0.1 second lasting short circuit fault at bus bar 6500. The grey curve which undergoes the greatest fluctuations shows the electrical frequency at bus bar 6500. The list of buses has been cropped, ref. caption under Figure 14 on page 43. The y-axis values are measured in Hz.

## 8 Discussion

This chapter presents considerations and discussions on the simulations that have been conducted and which were presented in chapter 7. The subchapters attempt to follow a tripartite structure; firstly the 350 MW case is presented, then the 1000 MW case, and finally the results from the two cases are hold together.

### 8.1 Power fluctuations

Power fluctuations simulations were run for the hours 0-12 (ref. Figure 3 on page 11) in two-hour portions (ref. subchapter 6.6). The hours 10-12 (note the 108 minutes initial offset described in subchapter 6.3.5) were judged to hold the most interesting power generation fluctuations since they included high power gradients, a large max/min span in output and three marked peaks.

The regulating power demand signals and the power generation in the four hydro power plants connected to bus bar 6500 were plotted (ref. Figure 12 and Figure 13 on page 41). These figures show that the implemented LFC control structure and the priority key work properly; firstly, the brown curve representing the total hydro power plants generation follows the red curve representing the power demand to the letter, and secondly; the lumped hydro power plant slowly shifts its setpoint and accordingly its generation to fit the new power demand, and so the regulating hydro power plants' (viz. Aura, Grytten and Jostedal) generation are, following their initial and fast response, reduced, preparing them to handle coming disturbances. This behaviour is in accordance with the desired one that was stressed in subchapter 6.7 and arranged through the priority key.

With 350 MW offshore wind power in service and connected to bus bar 6500, frequency excursions in the Nordel synchronous system model are efficiently bridled with the designated regulating power contributing hydro power plants and the implemented LFC scheme with  $\pm 175$  MW boundaries. The synchronous system frequency is well within Statnett's permissible limits during normal operation ( $\pm 0.1$  Hz, ref. subchapter 5.1 and Figure 14 on page 43).

The input wind data are the same for the two offshore wind farm models in the 1000 MW case of which the two generation patterns only differ by the gain (ref. subchapter 6.3.5). This is shown in Figure 19 on page 45 which displays the power generation for the same period of time, i.e. the hours 10-12. The  $\pm 175$  MW LFC boundaries from the 350 MW case were too tight with 1000 MW offshore wind power in service to keep the frequency within the desired  $\pm 0.1$  Hz belt, and so simulations were run with increased boundaries. With the initial generation conditions, 350 MW was available for upwards regulation (ref. Table 3 on page 38). Figure 20 and Figure 21 show examples of the Nordel synchronous system frequency with upper LFC boundaries of +350 MW and lower boundaries of -350 MW and -650 MW respectively. With the last mentioned boundaries fluctuations within a  $\pm 0.01$  Hz frequency band was for the most part obtained.

The offshore wind farm obviously imposes challenges on the operation of an electrical power system and one of these challenges can easily be recognized in the power fluctuations simulations that were run in subchapter 7.1.1 and 7.2.1 as a strong coherence between the Nordel synchronous system model frequency and the power generation in the offshore wind farm. The

simulation graphics of the subchapters show that such frequency fluctuations can be rendered harmless (in the meaning reduced to swings of sizes Statnett finds permissible) by implementing for instance a LFC control scheme; its just a question of allocating sufficient amounts of available balancing power. For the 1000 MW offshore wind power in service case that was simulated, to meet the normal operation limits of Statnett a latitude of 1000 MW (+350 MW upwards plus -650 MW downwards) was fully sufficient to comply with the 10 mHz requirement. To keep the LFC boundaries within reasonable limits with reasonable amounts of reserve power, this might be an indication that the power generation and the power gradients of the offshore wind farm should be limited. In practice, this could for instance be arranged by implementing the so-called power rate limitation control approach for upwards regulation and a combination of the power rate limitation and the so-called delta control principle for decrease in generation (Bolik, et al., 2005, ss. 136-138). These mechanisms are implemented in the Danish offshore wind farm Horns Rev 1.

The power demand was followed by well fitted generation in all simulated cases (ref. for instance Figure 12 on page 42). The proper following probably owes to the hydro power plants' generation characteristics in the main. Even a relatively high power gradient of an offshore wind farm (determined to 31.8 MW/min in subchapter 6.3.5) is exceeded by the power gradients of spinning machines in hydro power plants (Lind, 2009). Shifts in the setpoints of other machines in the system as a consequence of the fluctuations and successful choices of parameter values in the LFC PI controller might be another reason. Although the simulations showed that LFC was beneficially implemented in the Nordel synchronous system model, it shall be noticed that the success depend upon adequate LFC limits and available balancing power capacity; simulations showed that unpermitted frequency excursions may be the results of the PI controller in the LFC hitting its limits.

Some selected simulations results from the other two-hour periods between the hours 10-12 are enclosed in appendix 12.1.

## 8.2 Fault ride through

When the control system of a wind turbine is designed, an aim is to ensure that the unit will not trip because of the transient frequency gradients occurring in case of short-circuit faults on the high voltage network to which the unit is connected. The specifications of the aim are determined from the prevailing grid code of the network, and for Norway's part, these requirements are settled in Figure 5 on page 26. To test whether these requirements were violated or not, FRT simulations were performed by introducing 0.1 second lasting 3-phase short circuit faults on 7 selected bus bars of the Nordel synchronous system model. The 7 sets of simulations included fault on bus bar 6500 to which the offshore wind farm models were connected, fault on bus bars adjacent to bus bar 6500 and faults on bus bars located at more remote locations of the system with respect to bus bar 6500. All in all, the most severe frequency excursions on bus bar 6500 appeared when the fault was located at bus bar 6500 itself (simulations with a fault on the Swedish bus bar 3244 were exceptions). Some informative results from these simulations are thus reproduced in the subchapters 7.1.2 and 7.2.2.

The four curves of Figure 22 on page 47 show the behavior of the 650 MW offshore wind farm during the fault on bus bar 6500. Three of the curves were identical for the 650 MW and the

350 MW equivalent models, while the last curves showing the active power generation were identical in shape but diverged in maximum generation (650 MW and 350 MW). The other bus bars of the system were modestly affected. For the downwards curves; the reactive power generation spikes are attempts to counteract the voltage drop, while the delivered active power drops to 0 in accordance with the voltage drop. The spikes in the graphics showing reactive power owes to transient transitions caused by sudden voltage changes.

For all simulated cases; the offshore wind farm models start to swing as a consequence of the fault, but is well damped. A comparison of the voltage curves in Figure 15 on page 43 and Figure 5 on page 26 displaying the FRT requirements in Norway shows that the last ones are not violated during the fault for the 350 MW in-service case. A similar comparison for the 1000 MW case brings the same conclusion; the deviations in frequency were small and well damped. The proper behaviour during and after faults is probably attributed to how the Nordel synchronous system model is set up; all generators of the system are directly connected to the bus bars. When a fault occurs at bus bar X the generator connected to bus bar X has nowhere to deliver power and its speed and the system frequency increases. The increases are however not instantaneous and this owes to the inertia of the rotating generator and the constant flow in the turbine during the short time of the fault. When the fault is cleared the generator thus efficiently contributes in raising the voltage level and in stabilizing the frequency. This theory explains why bus bar 3244 is an exception; it is located adjacent to bus bar 6500 and its generator is separated from the bus bar by a transformer.

Some selected graphic results from the simulations are included in appendix 12.2.

### 8.3 Forced shut-down

Forced shut-down is a phenomenon that takes place in all wind farms from time to time, and thus it's interesting to investigate how it affects the network frequency. From the network side, forced shut-down principally appears like power fluctuations, the grid experiences variations in the power delivered from the offshore wind farm.

Forced shut-down simulations were run for the case with 350 MW in-service as shown in subchapter 7.1.3, with the downwards and upwards power gradients 31.8 MW/min and 15.9 MW/min respectively, as determined in subchapter 6.3.5. By manipulating the wind data used as input in the offshore wind turbine equivalent models to determine the power generation, forced shut-down was imitated. Subject to linear conditions, wind speeds corresponding to maximum and minimum generation were used as input at pre-calculated times. Forced shut-down simulations were not conducted with 1000 MW in-service because of the extensive time frame such simulations would span with the chosen power gradients.

Firstly, forced shut-down was simulated with upper and lower LFC boundaries of  $\pm 150$  MW. The LFC hit its boundaries, causing unacceptable frequency excursions, and so the upper boundary was extended to 350 MW and a new simulation was run. Even with the extended upper boundary the LFC hit its limit, and this saturation can be recognized as an irregularity just before 12 minutes on the frequency descending curve in Figure 18 on page 45. The frequency is about to recover prior to this event, but suffers from a too strict upper boundary limit on the LFC and drops another few  $\mu\text{Hz}$ . Some conclusions can be drawn from this:



LFC definitely (and obviously) helps to withhold system frequency excursions beyond the acceptable limits that were mentioned repeatedly in subchapter 8.1, compared to a situation without a functioning LFC. The simulations show moreover that more regulating power shall be allocated if there is risk or probability of a forced shut-down, or in other words attention must be given to gale warnings.

Some selected graphic results from the simulations are included in appendix 12.3. The appendix includes results showing the system frequency with the LFC set as out of service and the system frequency with lower upper boundary of the LFC, the power demand signals of the LFC control and the active power generation in the hydro power plants during the forced shut-down. Some conclusions have been drawn fully or partly on basis of these simulation results.

## 9 Conclusion

In order to comply with governmentally announced greenhouse gas emission reductions goals and to consolidate an independent and stable electric power and energy supply, Norway must increase its installed renewable energy based power generation capacity. Profitability estimations, today's available technical solutions and regulations concerning preservation of natural resources leave construction of new small hydro power plants behind as the most plausible alternative together with construction of wind farms. Global trends and the public opinion indicate that future wind farms in Norway will be located offshore. The assumption is supported by the recent handing out of a concession to an offshore wind farm project for the first time in Norwegian history. The projects name is Havsul 1 and the licence involves construction of 350 MW offshore wind power. Havsul 1 will be located in Mid-Norway, which is the region in Norway where the TSO Statnett is most concerned about their ability to execute their task of assuring safety of power supply in the future. The concern owes to lack of generation capacity and transmission constraints.

Experience show that commissioning of large offshore wind farms will impose power balance associated challenges on the TSO. By applying a slightly modified model developed by Sintef of the Nordel synchronous system in the power simulation tool DIGSILENT PowerFactory, grid connection of two offshore wind farms of 350 MW and 1000 MW to a bus bar representing Mid-Norway were investigated, targeting reduction of frequency excursions. To execute the reduction task, a so-called centralised load frequency control (LFC) scheme was implemented and four hydro power plants were designated to provide regulating power pursuant to a priority key that used their response times as input. To simulate power fluctuations in the time span of hours, real time wind data acquired from the Danish offshore wind farm Horns Rev 1 was used as input in the offshore wind farm model. Some short term fault ride through and forced shut-down simulations of the offshore wind farm were also conducted.

The power fluctuations simulations showed that LFC is a well-fitted tool for bridling frequency excursions caused by fluctuating power generation in an offshore wind farm. During the power fluctuations, which were of a particularly challenging kind, the system frequency complied with Statnett's normal operation requirements of  $50 \pm 0.1$  Hz. A less fluctuating system frequency, for the most part within a  $50 \pm 0.01$  Hz band, was even obtained. However, to solve this task, the LFC occupied quite massive amounts of regulating power. With 1000 MW offshore wind power in-service, restricted by the LFC, 1000 MW of hydro power generating capacity was used to meet the  $50 \pm 0.01$  Hz band. Utilizing the tolerated  $\pm 0.1$  Hz band fully would reduce the need for available regulating power capacity substantially.

Some short-term stability analysis simulations were also run; more exactly 3-phase short circuit faults were introduced at selected bus bars in the system to test the fault ride through capability of the offshore wind farms. The faults were introduced at one bus bar at a time and cleared after 0.1 seconds. The simulations showed that the greatest system frequency excursions took place when the short circuit fault occurred at the bus bar to which the offshore wind farm model was connected, but a comparison between the FRT requirements curve in Norway and the offshore wind farm voltage showed that the FRT requirements were not even in that case violated. The frequency excursions were all in all small, a behaviour that is probably attributed to model setup; all bus bars have generators directly connected to themselves, and these machines efficiently contribute in maintenance of the frequency and voltage levels.

The simulated forced shut-down did as expected neither impose great challenges on the system operation regarding frequency deviations. The problem can be regarded as a variant of the power fluctuations and the simulations thus brought similar results. The forced shut-down simulations did however show that attention must be given to gale warnings.

Even though some FRT and forced shut-down simulations were conducted, the main objective of this thesis was to investigate whether or not LFC was suitable for bridling frequency excursions in the Norwegian power system caused by fluctuating power generation in an offshore wind farm by levelling power generation with power demand. The implemented LFC scheme solved the task efficiently; a result that isn't too surprising since LFC has been used successfully in Europe for many years. The Norwegian power system is based on fast responding hydro power and should thus be at least as well-equipped for handling commissioning of offshore wind power as the continental power system. The results may however be useful for illustration of another circumstance; a massive expansion in commissioned wind power may raise a discussion about whether the amounts of automatically activated reserves as of today are adequate; the frequency controlled normal operation reserve as it's put down in the Nordic Grid Code is substantially smaller for Norway's part than the amounts of reserve power that were required by the LFC in this thesis, but then again, Statnett's frequency requirements were more than fulfilled. In any case does LFC seem to be a useable tool if today's handling of secondary control in the Nordel synchronous system for some reason becomes insufficient in the future.

It shall be noticed that the power system model used in this thesis is very simple compared to the real power system and not particularly suited for short-term stability analysis simulations. Some circumstances glorified the simulation results, like the assumption of static loads and a static power plan, while some, like the wind data, represented a worst case scenario.

## 10 Further work

Two different approaches to further work unfold; the first one which treats improvements that would increase the value of the investigations of this thesis and the second one which addresses problems arisen during the work with the thesis.

One approach could be to improve the exactness of the model that has been used in the investigations of this thesis. The model of the Nordel synchronous system is very simple as compared with the factual system, and the wind data that have been used to determine the power generation in the wind farm are taken from another area. The PI controller of the LFC should also be tuned to ensure optimal load-following; its parameter values were picked randomly within UCTE's recommended interval. The LFC scheme that was implemented in PowerFactory could be expanded to include also the frequency error. The decentralized hierarchical and pluralistic LFC structures should also be tested.

It's probably more interesting to dig into some of the challenges that have arisen during the work with this thesis. Problems to be addressed:

- A more thorough analysis of the utility value of new wind power projects in Norway.
- Investigations on more detailed power system models, with generators giving more control input options.
- FRT investigations with other wind turbine technologies.
- Investigations using local wind series with a suitable time-frame and resolution.

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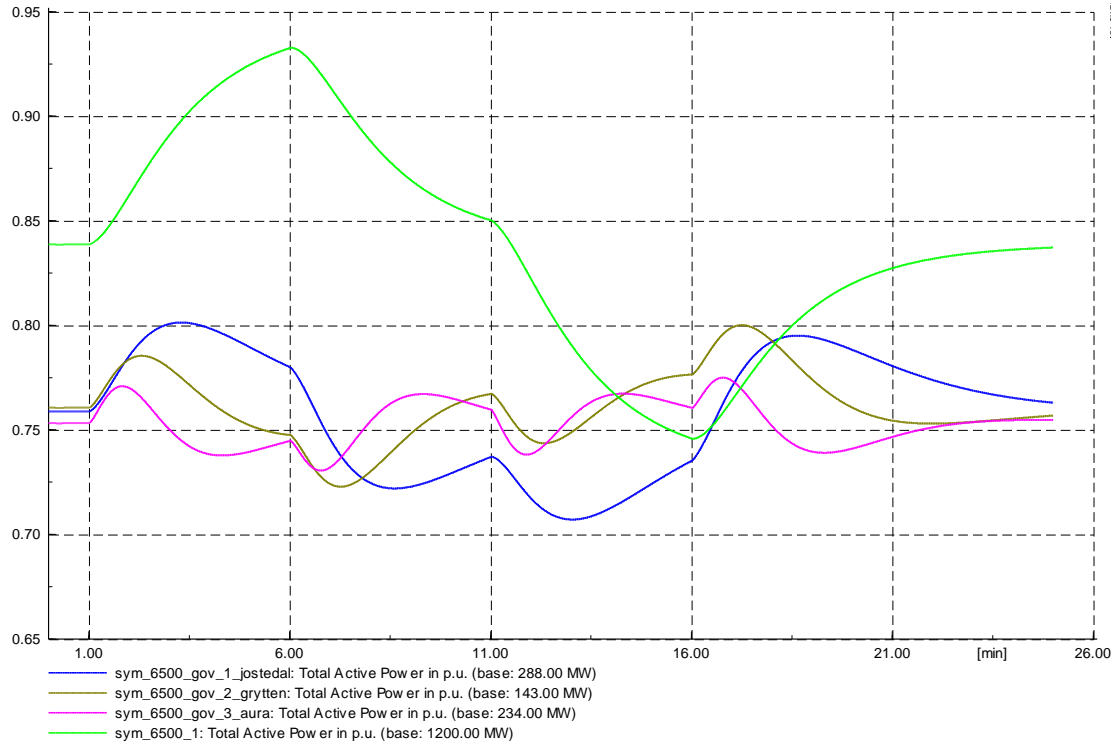
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## 12 Appendix

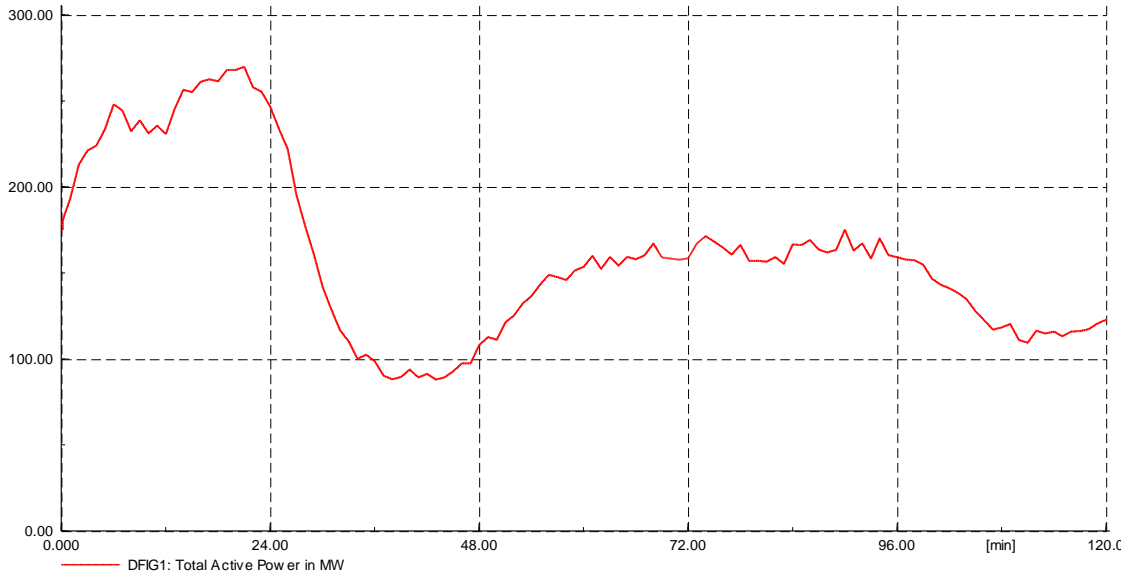
The appendix contains miscellaneous graphic results from power fluctuations, fault ride through and forced shut-down simulations, spread over three subchapter-appendixes. Finally, typical governor parameter values of the hydro power plants of the grid model are presented.

The figure below does not belong to the previously mentioned partitions; it shows the active power generation in the hydro power plants connected to bus bar 6500 during the step response test described in subchapter 6.7.

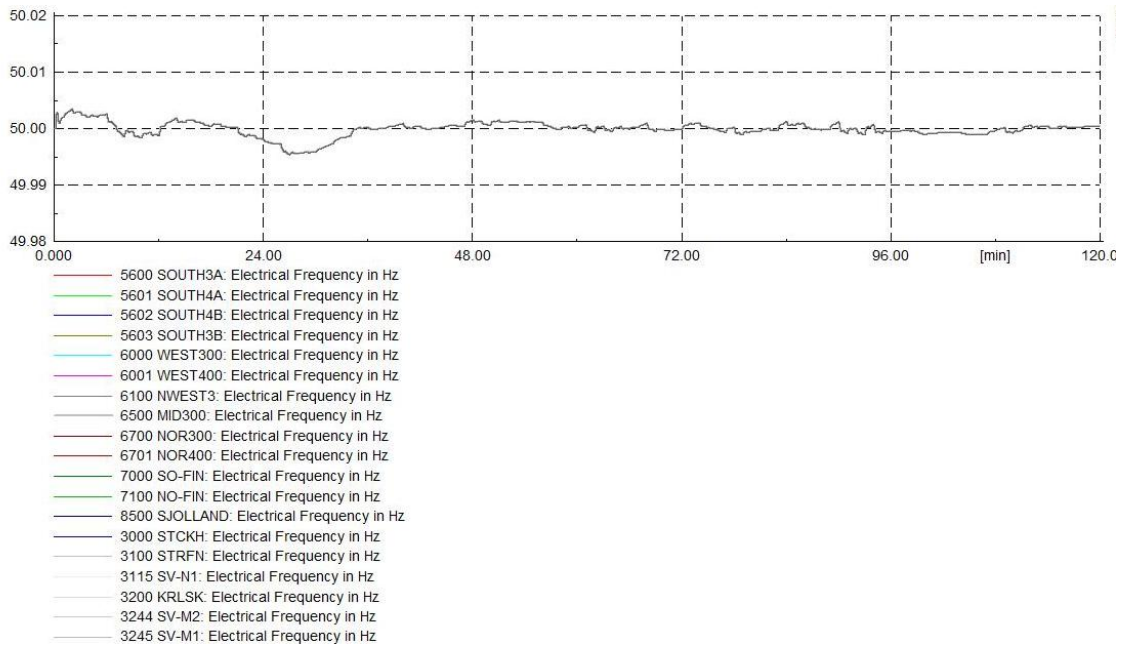


**App. figure 1** Active power generation in the four hydro power plants connected to bus bar 6500 during the step response test conducted in subchapter 6.7. The composite LFC model was disconnected during the test. A clarifying note to the text describing the green curve; the curve shows the active power generation in the lumped hydro power plant, not the total active power generation in the three other hydro power plants as the text may mislead the reader to think. The y-axis values are measured in pu.

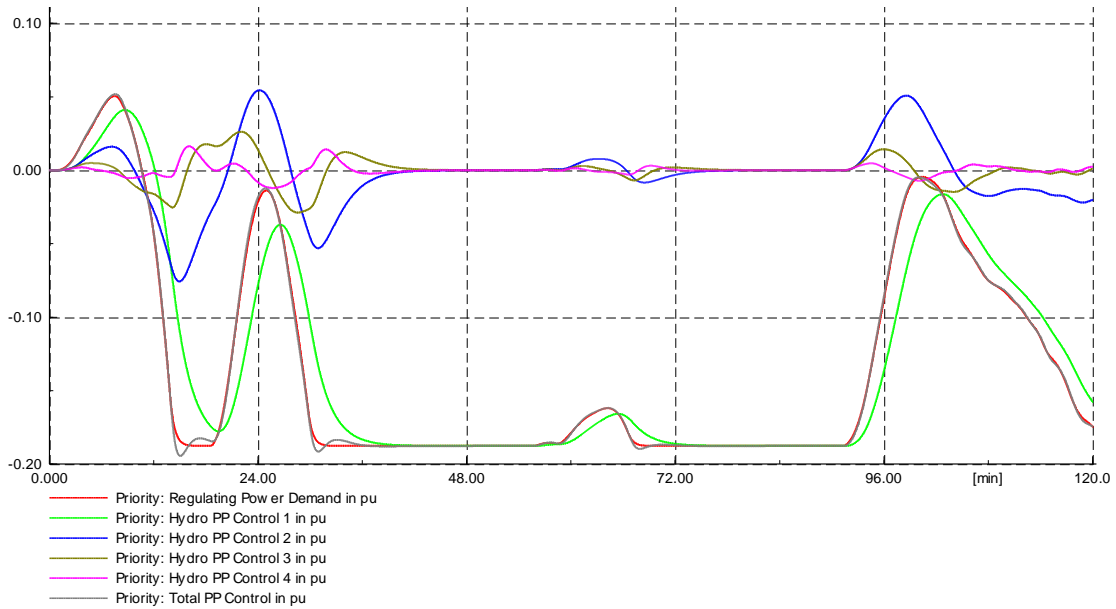
## 12.1 Power fluctuations



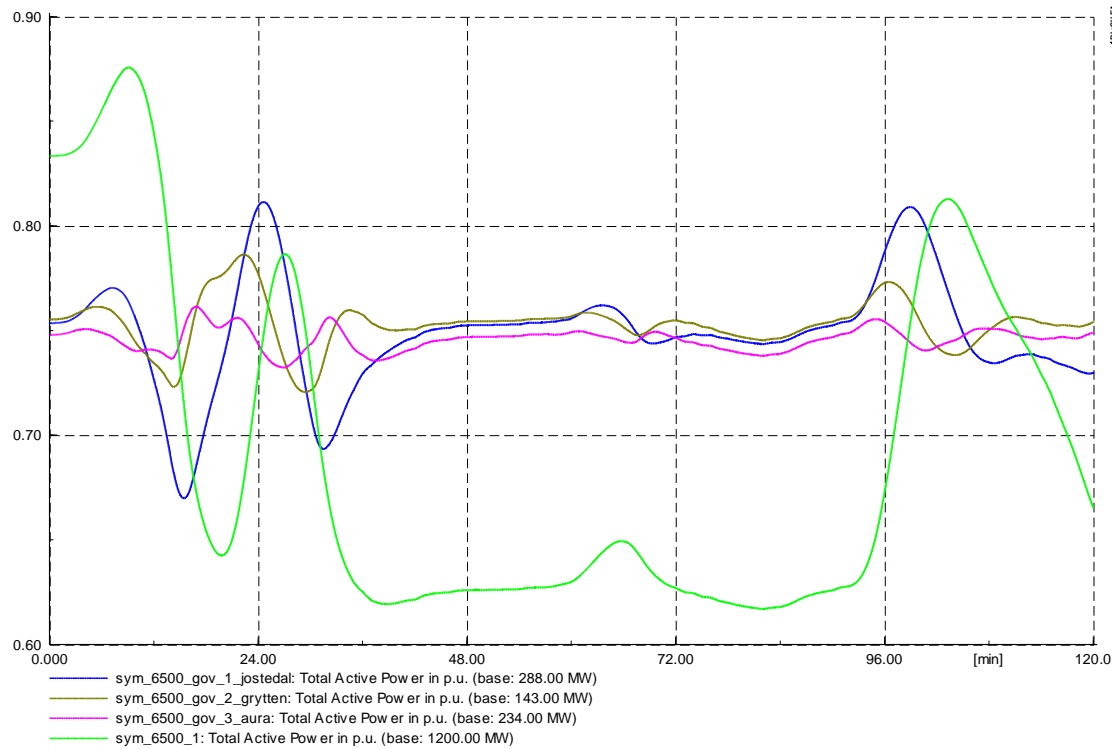
**App. figure 2** The red curve shows the active power generation in the 350 MW offshore wind farm model during the hours 0-2. The figure is reproduced in order to exemplify why the hours 10-12 was judged to contain the most interesting power generation. The y-axis values are measured in MW.



**App. figure 3** The curve shows the electrical frequencies of the bus bars in the Nordel synchronous system model during the hours 0-2 for the case with 350 MW offshore wind power in-service. The list of buses has been cropped; the frequencies of all the bus bars in the power system model are plotted in the graph, but the curves are congruent since all the buses are part of the same synchronous system. The figure is reproduced in order to emphasize the point demonstrated in the above figure showing the active power generation during the same time period. The y-axis values are measured in MW.

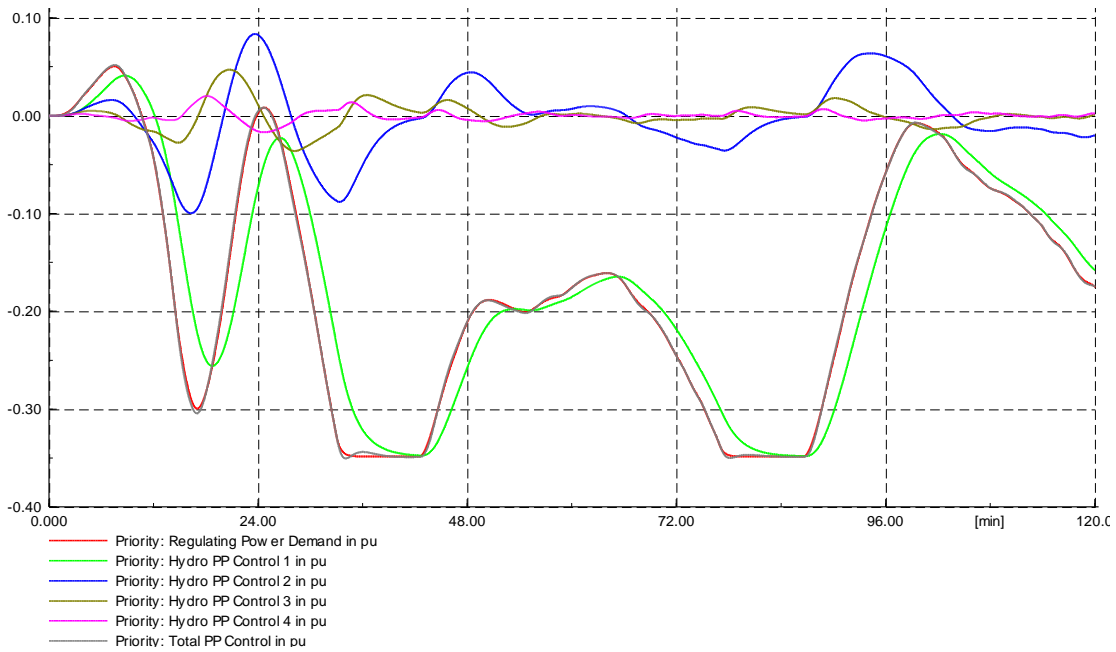


App. figure 4 Regulating power demand signals sent to the hydro power plants connected to bus 6500 from the LFC during the hours 10-12 (ref. Figure 9 on page 37) with 1000 MW offshore wind power in-service. The red curve represents the total demand and the brown curve the total contribution from all four hydro power plants connected to bus bar 6500. The individual control signals for the hydro power plants Aura, Grytten, Jostedal and the lumped generation are pink, brown, blue and green respectively. The y-axis values are measured in pu referred to the installed generation capacities (ref. Table 3 on page 38). The LFC boundaries were  $\pm 350$  MW.

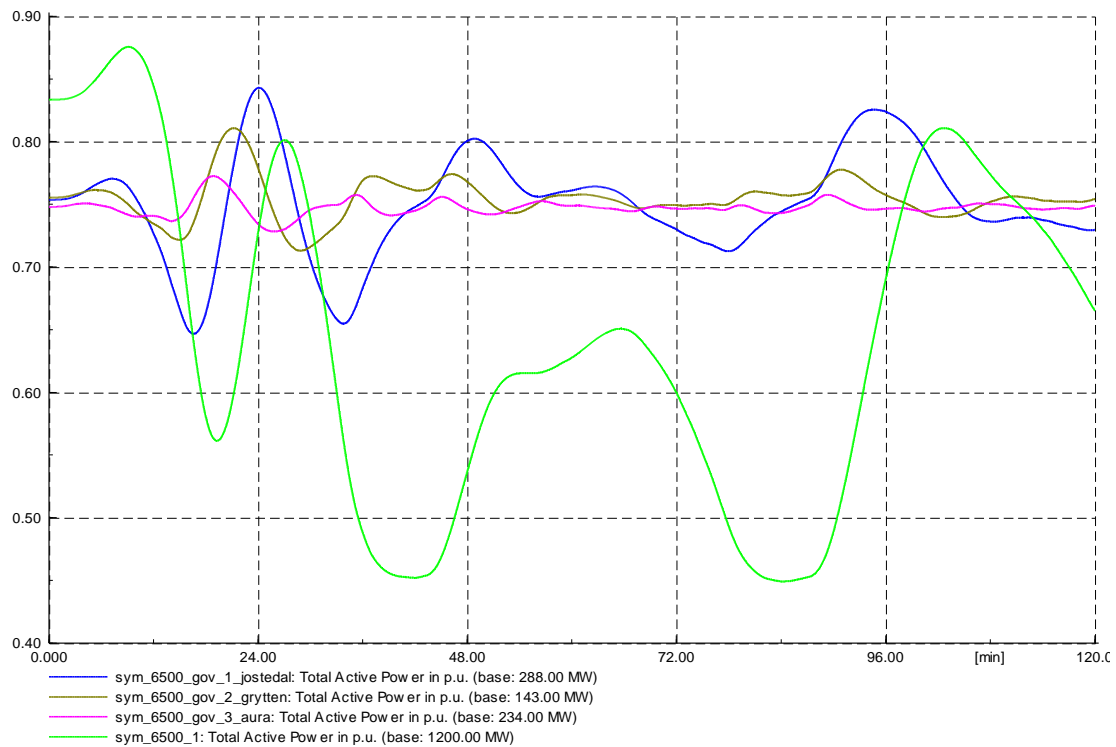


App. figure 5 Active power generation in the hydro power plants connected to bus bar 6500 during the hours 10-12 with 1000 MW offshore wind power in-service. The relation between curve colors and hydro power plants is shown below the figure. While

Figure 12 showed the regulating power demand signals, these curves show the factual power generation (determined on the basis of the power demand signals). The y-axis scale is measured in pu referred to the maximum generation capacity bases that are shown below the figure. The LFC boundaries were  $\pm 350$  MW.



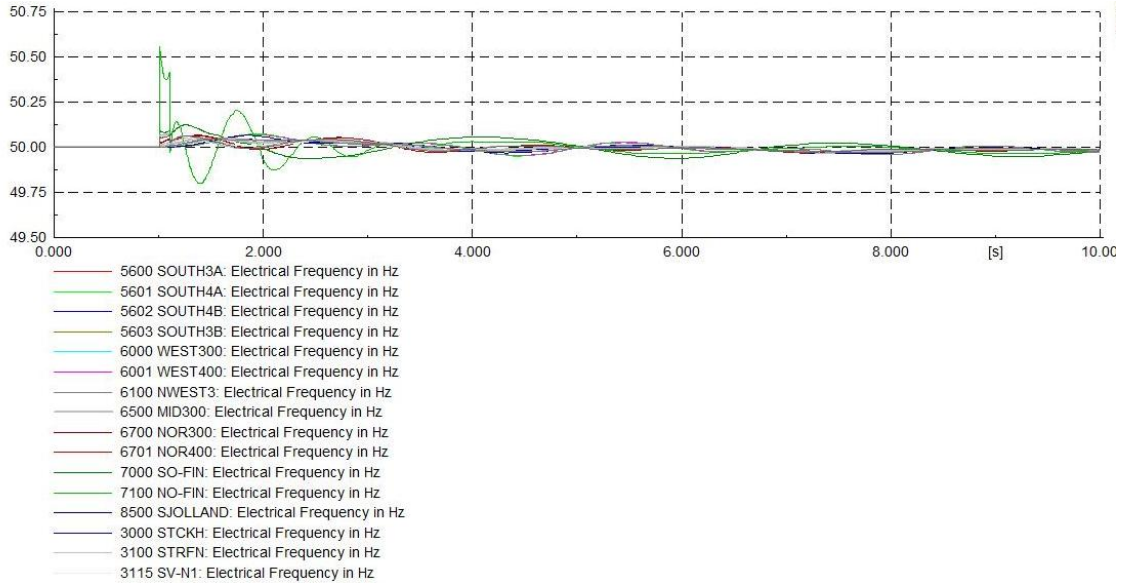
App. figure 6 See caption for App. figure 4 on page 62 which is valid also for this figure, except of the lower LFC boundary that were  $-650$  MW for this simulated case.



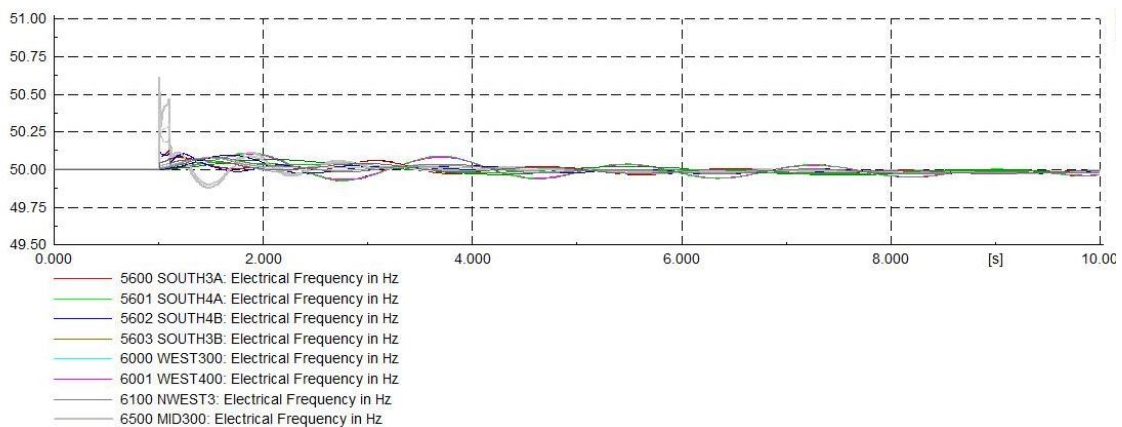
App. figure 7 See caption for App. figure 5 on page 62 which is valid also for this figure, except of the lower LFC boundary that were  $-650$  MW for this simulated case.

## 12.2 Fault ride through

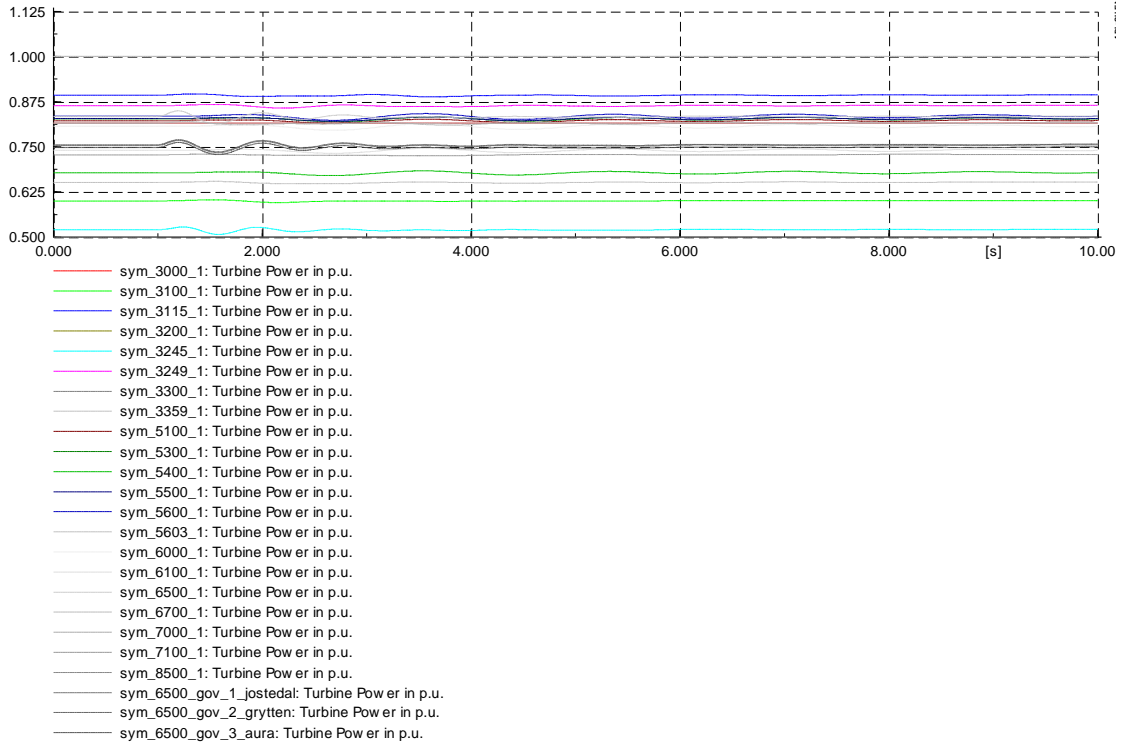
The simulations included in this appendix are enclosed because the discussions of subchapter 8.2 somehow are partly or fully based on what they show.



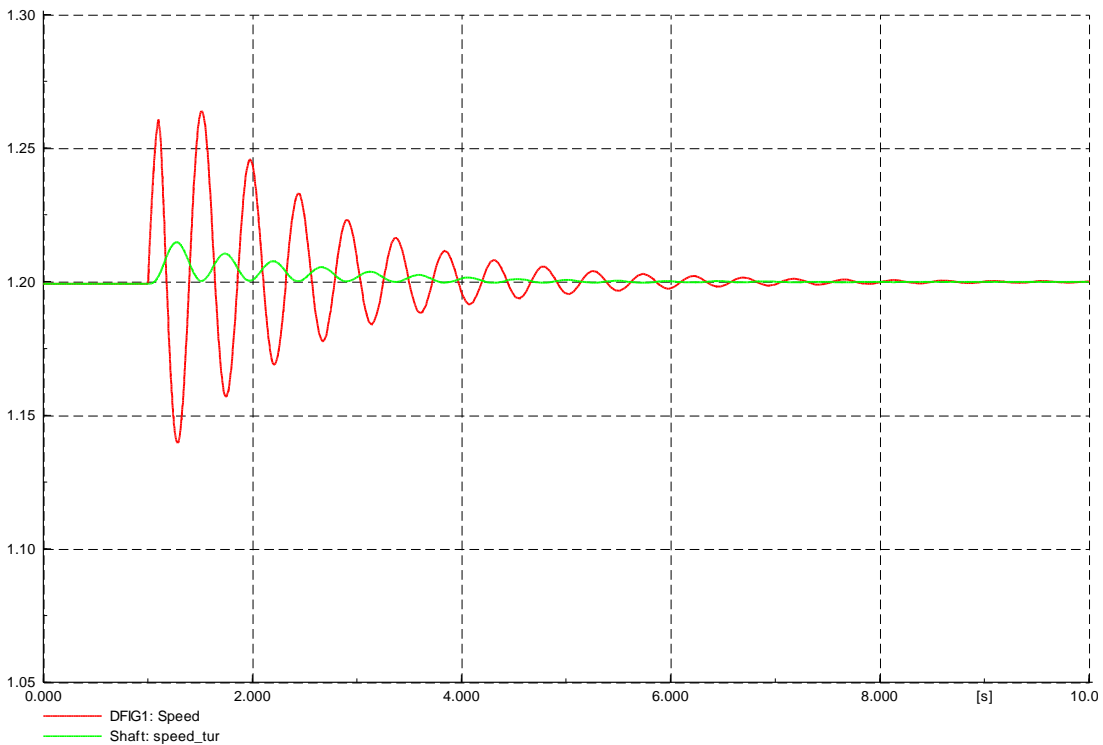
**App. figure 8** Electrical system frequencies of the bus bars in the Nordel synchronous system model during a 3-phase, 0.1 second lasting short circuit fault at bus bar 7100 which is one of the bus bars that represent Finland. The green curve which undergoes the greatest fluctuations shows the electrical frequency at bus bar 6500. The figure has been included to exemplify that the frequency of bus bar 6500 to which the offshore wind farm model is connected fluctuates modestly during a 3-phase, 0.1 second lasting short circuit fault, compared to the fluctuations that followed such a fault when it occurred at bus bar 6500 itself. The list of buses has been cropped, ref. caption under Figure 14 on page 43. 350 MW wind power is in-service. The y-axis values are measured in Hz.



**App. figure 9** Electrical system frequencies of the bus bars in the Nordel synchronous system model during a 3-phase, 0.1 second lasting short circuit fault at bus bar 3244. The grey curve which undergoes the greatest fluctuations shows the electrical frequency at bus bar 6500 compared to the fluctuations that followed such a fault when it occurred at bus bar 6500 itself, as accounted for in subchapter 8.2. The list of buses has been cropped, ref. caption under Figure 14 on page 43. The y-axis values are measured in Hz.

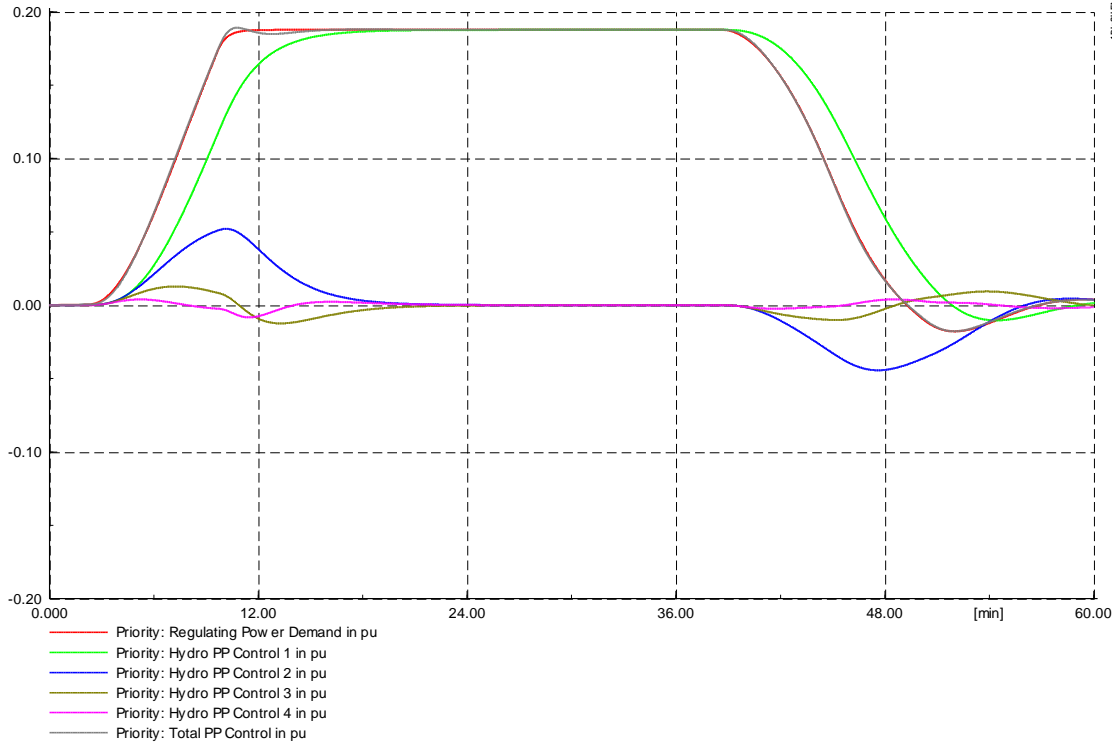


App. figure 10 The curves of the figure show the turbine power of all power plants of the Nordel synchronous system model during a 3-phase, 0.1 second lasting fault occurring at bus bar 6500. The y-axis values are measured in pu.

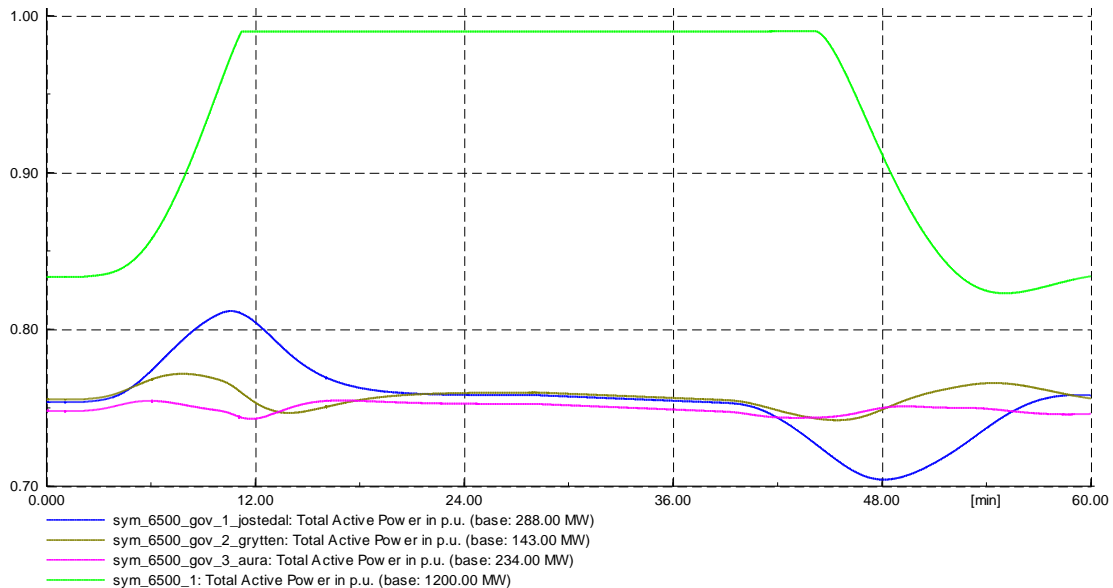


Offshore wind turbine generator (red) and shaft (green) rotational speeds during a 3-phase, 0.1 second lasting short circuit fault occurring at bus bar 6500. The y-axis values are measured in pu.

## 12.3 Forced shut-down



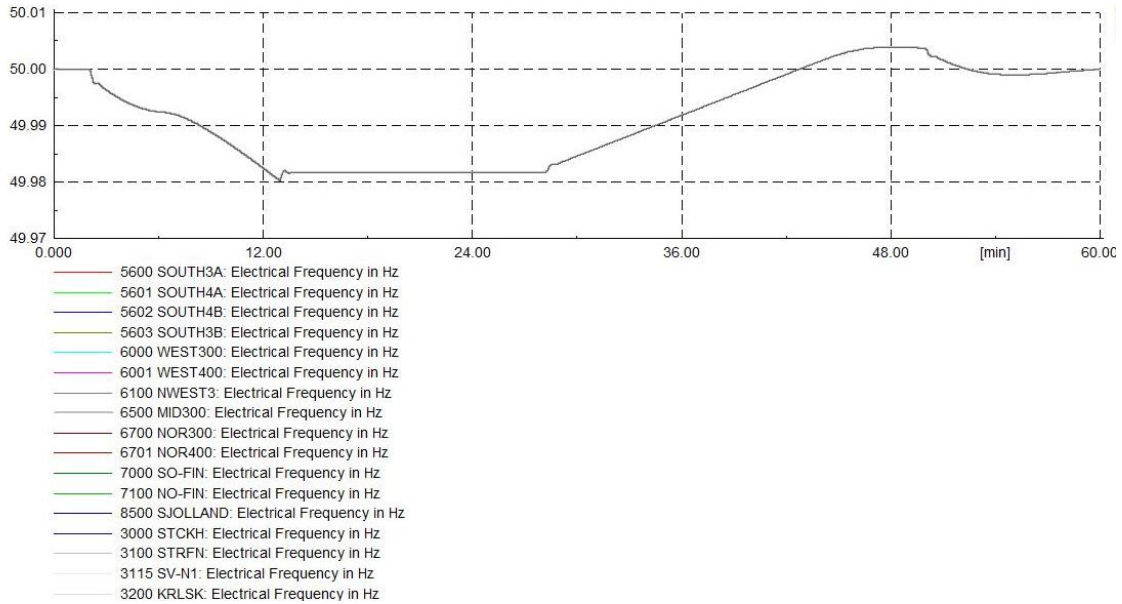
App. figure 11 Regulating power demand signals sent to the hydro power plants connected to bus 6500 from the LFC during forced shut-down and subsequent restart of the 350 MW offshore wind model. The red curve represents the total demand and the brown curve the total contribution from all four hydro power plants connected to bus bar 6500. The individual control signals for the hydro power plants Aura, Grytten, Jostedal and the lumped generation are pink, brown, blue and green respectively. The y-axis values are measured in pu referred to the installed generation capacities (ref. Table 3 on page 38). The LFC boundaries were  $\pm 350$  MW.



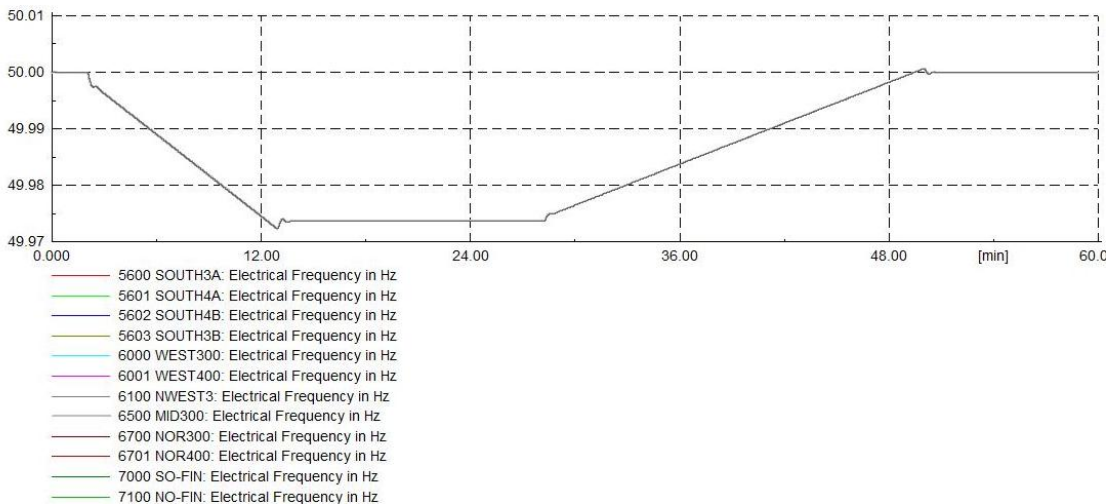
App. figure 12 Active power generation in the hydro power plants connected to bus bar 6500 during forced shut-down and subsequent restart of the 350 MW offshore wind model. The relation between curve colors and hydro



power plants is shown below the figure. While Figure 12 showed the regulating power demand signals, these curves show the factual power generation (determined on the basis of the power demand signals). The y-axis scale is measured in pu referred to the maximum generation capacity bases that are shown below the figure. The LFC boundaries were  $\pm 350$  MW.



App. figure 13 The curve shows the electrical frequencies of the bus bars in the Nordel synchronous system model during forced shut-down and subsequent restart of the 350 MW offshore wind model. The list of buses has been cropped; the frequencies of all the bus bars in the power system model are plotted in the graph, but the curves are congruent since all the buses are part of the same synchronous system. The upper LFC boundary was +150 MW, and the y-axis values are measured in MW.



App. figure 14 See caption for App. figure 13 which is valid also for this figure, except of the all aspects concerning the LFC, because the LFC was set as out of service during this simulation.

## 12.4 Hydro power governor values

Name: HYGOV\_5300

Model Definition: Library\pcu\_HYGOV\_RP

Out of Service       A-stable integration algorithm

	Parameter	
▶ R	Permanent Droop [p.u.]	0.06
r	Temporary Droop [p.u.]	0.4
T <sub>r</sub>	Governor Time Constant [s]	5.
T <sub>f</sub>	Filter Time Constant [s]	0.05
T <sub>g</sub>	Servo Time Constant [s]	0.2
T <sub>w</sub>	Water Starting Time [s]	1.
A <sub>t</sub>	Turbine Gain [p.u.]	1.1
P <sub>turb</sub>	Turbine Rated Power (0 = p <sub>turb</sub> =p <sub>gen</sub> ) [MW]	0.
D <sub>turb</sub>	frictional losses factor pu [p.u.]	0.5
dP		0.
df		0.1
Prat		2.75
frat		50.
T <sub>fr</sub>		20.
qnl	No Load Flow [p.u.]	0.1
G <sub>min</sub>	Minimum Gate Limit [p.u.]	0.
Qnl	No Load Flow [p.u.]	-999.

Buttons: OK, Cancel, Events

App. figure 15 Typical parameter values of the governors of the hydro power plants in the grid model described in subchapter 6.4.