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Inertia and FCR in the Present and Future Nordic Power System

Inertia Compensation

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I. PROBLEM DESCRIPTION

The future power system will include variations in production pattern and new sources of electricity production. The common hypothesis is that the kinetic energy, or the inertia, in the power system will decrease and that this will affect the operational system security. In a market perspective this can be a case. But what about the technology, will the inertia be too low? And if this becomes the reality, how is it best compensated for?

A part of the task is to study the frequency containment reserves (FCR) requirements and levels of inertia. What is most critical? How is the stability affected? The following scenarios will be investigated

- One reference scenario to tune the model.
- A summer day that has occurred.
- A future summer scenario.

Another task is to identify potential and realistic sources for inertial response in the future power system. How will the compensation influence the grid, e.g. bottlenecks/congestions and the distribution of the inertia? Will increased volumes of FCR give the same result? Economic perspectives will not be considered.

A model for simulations is provided. Simulation tool that will be used is PSS®E.

The topic for this thesis is partly the same as fellow student, Beate Nesje. Some of the same scenarios will be studied, but she will be running simulations in Simulink.

Contact in Statnett: Bjørn Bakken and Alexander Jansson.

II. Preface

This thesis is the final work submitted to fulfill the degree Master of Science (MSc) at the Norwegian University of Science and Technology (NTNU). The thesis is worth 30 credits.

I want to thank my supervisor, Professor Kjetil Uhlen at NTNU. I really appreciate all his valuable advices and guidance during this work. In addition Lester Kalemba and Dinh Thuc Duong, also at NTNU, need to be mentioned for support in PSS®E. My contacts in Statnett have been Bjørn Bakken and Alexander Jansson. I am grateful that they proposed this topic and helped me formulate an interesting problem description. They have also been very helpful by providing data and given me feedback on the work.

I am also thankful for the cooperation and discussions of the topic with fellow student Beate Nesje. Other fellow students, friends and family must be mentioned for always be supportive.

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III. ABSTRACT

The power system characteristics are changing and new power production in the Nordic countries is dominated by modern wind turbines and small scale hydro power. These are wind turbines that are electrically decoupled from the power grid through converters and hydro units below 10 MW with less inertia constants. In Sweden the nuclear power will most likely be reduced in the years to come. Towards 2020 the HVDC capacity connected to Norway will be more than doubled as two new 1400 MW cables to Germany and Great Britain will come in operation. Overall this results in less rotating mass in the power system, creating a lower inertia level. Whether this will be a problem or not is crucial for operational strategies and system security. Especially low load scenarios are of concern, e.g. a summer day with high import, relatively high wind production and where large hydro and thermal units are off-line.

There are requirements for the frequency reserves, but there are no requirements regarding inertia. Today the frequency containment reserves which are the primary reserves are organized as two separate mechanisms. FCR-N is for normal operation between 49.9-50.1 Hz with a requirement of 6000 MW/Hz, while FCR-D is for disturbances and is active between 49.9-49.5 Hz with a requirement of 3000 MW/Hz. The FCR-D response should be 50 % activated in 5 seconds and 100 % activated in 30 seconds. In addition there are a transient limit of 49.0 Hz and a steady state limit of 49.5 Hz. The question is whether these requirements will secure sufficient levels of inertia or if other measures must be taken.

Possibilities of inertia compensation have been studied and simulated. Three alternatives were considered; synchronous condensers, synthetic inertia on wind turbines and synthetic inertia on HVDC. Synchronous condensers are a well established technology, while the synthetic inertia is a modern concept based on controls of power electronics and is still developing.

Simulations were conducted in PSS®E using an aggregated Nordic model (Nordic44). Three scenarios were considered. One of these was a reference scenario used to tune the model and included a recent outage of 1110 MW nuclear power in Sweden. Scenario 2 was a summer day from 2013 where production and load were low and import relatively high. This scenario was included to get an impression of the conditions "today", as this is necessary to better estimate the future. The third scenario was a future scenario. The new HVDC cables in Norway were included and a summer day in 2020 with high import was considered in three versions. The first one (3a) has a share of production similar of "today", the next (3b) was based on Statnett's worst case production portfolio including 20 % wind. The last one (3c) is similar, but includes the possibility of synthetic inertia on both the installed wind and the VSC HVDC cables.

When tuning the model response, several weaknesses of the Nordic44 model were revealed. First of all voltage levels and lines were not up to date. Second, different area division in the model made it difficult to distribute production and load data. At last the capacity in some areas had to be expanded. In total this resulted in a load flow not reflecting the real situation. The aim of the work was not to improve the model and the dynamic analyses were conducted without too many changes. The model is simple and advanced functions as HVDC emergency power and parameter changes on governors were not included. Voltage dependence of the load appeared to be another factor of great influence in the model. The voltage regulation in the model is most likely not sufficient and it is probably another model weakness. The above mentioned factors might influence the results of the simulations.

The same outage (1110 MW) was tested throughout the thesis. During the simulations both scenario 2 and 3 revealed low levels of inertia (135 to 104 GWs). Some outages (2 and 3b) were also simulated from an initial frequency of 49.9 Hz as a "worst case scenario" to check the FCR-D requirements. Doing so the frequency of both scenarios ended up below the transient limit, even though the outage was less than the dimension incident. Adjusting the droop settings mainly affected the steady state frequency. The FCR-D requirement of 50 % activation in five seconds was not met. Another option was considered; more hydro production on line at lower output. This increased both inertia and FCR and was therefore efficient. Anyway, this is not a desired way to increase the inertia as energy is assumed spilled. However this alternative met the 50 % activation after five seconds requirement with 40 % (of P_{Max}) output on all hydro generators. This is remarkable as it does not reflect a realistic operation situation and is probably due to a slow model response.

For inertia compensation synthetic inertia appeared to be a better alternative than synchronous condensers. This is due to the low inertia constant of the synchronous condensers compared to the flexible gain value of the synthetic inertia. Furthermore, the synthetic inertia needs more attention, especially the possibilities on HVDC cables. In this thesis a simplification was made; the wind model was also used to model the synthetic inertia from HVDC. As only import is studied this is possible. The disadvantage is that since the wind model is based on the mechanics of a wind turbine, the power taken from the rotor must be recovered. This is not the case for HVDC cables as the connecting country can be assumed unlimited. Wind plans in Norway are rather unclear and the government's target of 3000-3500 MW installed wind within 2020 might be too optimistic. However, the mentioned 2800 MW HVDC cables will be built and are therefore a more realistic source of synthetic inertia in Norway.

Whether the FCR requirements will secure the levels of inertia is difficult to say from the model. The five second activation requirement seems to be very strict for these simulations using this model. Achieving 50 % after five seconds required lots of hydro power online at low output and this also coped with the other requirements. Anyway, this might be due to a slow model response and should not be seen as a finding. The structure of the FCR is a topic under investigation by the TSOs today. From these analyses the division between FCR-N and FCR-D do not seem to be optimal. Especially remarkable is how to relate the output requirement based on time with the requirement of frequency bias available. Clearer definitions of the different requirements or restructuring should be considered. As low inertia levels were reveled both in the past and future scenario action regarding inertia should be taken. A need to control the amount of inertia online is inherent. Therefore, possibilities for inclusion of inertia in the FCR market or creation of a separate market should be investigated.

IV. SAMMENDRAG

Kraftsystemet er i endring og ny kraftproduksjon i Norden domineres av moderne vindturbiner og småskala vannkraft. Nyere vindturbiner er elektrisk separert fra kraftnettet via frekvensomformere og bidrar dermed ikke med roterende masse, mens småskala vannkraft er produksjonsaggregat under 10 MW med lavere treghetstidskonstant. Frem mot 2020 bygges det mye ny HVDC-kapasitet til Norge og kabler til Tyskland og Storbritannia, hver på 1400 MW, vil komme i drift. I tilegg vil Svensk kjernekraft mest sannsynlig reduseres i årene fremover. I alt betyr dette mindre roterende masse, altså mindre treghet, i kraftsystemet. Dette kan bli kritisk for driftsikkerheten. Med tanke på lav roterende masse er særlig lavlastsituasjoner kritiske og et typisk eksempel er en sommerdag med høy import og mye vindproduksjon, samtidig som store vannkraft- og kjernekraftgeneratorer er frakoblet.

I dag finnes det krav til frekvensreserver, men ingen krav som omhandler treghet. Primærreservene (FCR) er delt i normaldriftsreserve (FCR-N) og forstyrrelsesdriftsreserve (FCR-D). FCR-N er aktiv i frekvensbåndet 50.1-49.9 Hz og kravet er en regulerstyrke på 6000 MW/Hz, mens FCR-D er for frekvensområdet 49.9-49.5 Hz og skal være 3000 MW/Hz. For FCR-D skal 50 % være aktivert etter 5 sekunder og 100 % etter 30 sekunder. I tillegg skal frekvensen aldri falle under 49.0 Hz og aldri stabilisere seg lavere enn 49.5 Hz. Et sentralt spørsmål er om disse kravene vil sikre nok treghet i kraftsystemet eller om andre strategier må iverksettes.

Blant kompenseringsalternativer for lav roterende masse ble tre alternativer vektlagt; roterende (synkron) fasekompensator, syntetisk treghet på vindturbiner og syntetisk treghet på HVDC-kabler. Førstnevnte baserer seg på godt etablert teknologi, mens de resterende er basert på kontroll av moderne kraftelektronikk og er fortsatt i utvikling.

Simuleringer ble utført i PSS®E på en aggregert nordisk modell (Nordic44). Tre scenarioer ble studert. Det første kun for å stille modellresponsen fra et utfall av 1110 MW kjernekraft i Sverige fra mars 2015. Scenario 2 er en sommerdag fra 2013 med lav last og relativt høy produksjon. Dette ble inkludert for å undersøke en driftssituasjon som allerede har skjedd og representerer status "i dag". Scenario 3 er et fremtidsscenario som representerer en sommerdag i år 2020 hvor de nye HVDC kablene er i drift og importen er høy. Scenarioet er videre delt i tre underscenarioer; hvor det første (3a) har produksjonsfordeling som "i dag", det neste (3b) er basert på Statnetts "verste fall" produksjonsfordeling for 2020 med 20 % vind inkludert og det tredje (3c) er tilsvarende, men her er det mulighet for syntetisk treghet både på vindturbiner og på HVDC-kabler.

I arbeidet med å stille modellresponsen ble flere svakheter ved Nordic44 modellen funnet. For det første er ikke spenningsnivåene og linjene oppdatert med tanke på dagens situasjon. Områdeinndelingen i modellen avviker fra Elspotområdene og fordeling av last og produksjon ble noe problematisk. I tillegg måtte kapasiteten økes i visse områder da initial produksjon ikke var tilstrekkelig. Summen av dette ble en lastflyt som ikke reflekterte scenarioene korrekt. Siden formålet med arbeidet ikke var å forbedre modellen ble de dynamiske analysene utført uten mange endringer. Det må og nevnes at modellen er enkel og avanserte systeminnstillinger, som HVDC-nødeffekt og parameterskifte på vannkraftregulatorer, ikke er inkludert. I tillegg viste lastens spenningsavhengighet seg å være en avgjørende faktor for frekvensresponsen. Dette tyder på for dårlig spenningsregulering i modellen og er mest sannsynlig en modelleringssvakhet. Alle overnevnte faktorer vil påvirke resultater fra simuleringene.

Det samme utfallet (1110 MW) ble testet i alle scenarioene. I både scenario 2 og 3 var det lite treghet i systemet (mellom 135 og 104 GWs). Utfallene (2 og 3b) ble også testet fra en startfrekvens på 49.9 Hz, da dette er et reelt driftstilfelle som representerer "verste fall" versjon. Dette gjør det også mulig å studere kun FCR-D. Resultatet ble at begge scenarioene falt under 49.9 Hz, selv om utfallet er mindre enn dimensjonerende feil. Statikkinnstillingene ble forsøkt justert, men som forventet påvirket dette hovedsakelig den stasjonære frekvensen. FCR-D kravet om 50 % aktivering innen fem sekunder ble ikke oppfylt. Som et tiltak for å oppfylle dette ble det forsøkt å skru på mer vannkraftkapasitet med lavere produksjon. Dette var effektivt da både FCR og roterende masse i systemet økte. Uansett er dette en uønsket måte å øke tregheten på, da man anser slik drift som sløsing av energi. Ved nok reduksjon (alle vannkraftverk kjørte på 40 % av P_{Max}) var 50 % kravet innen fem sekunder oppfylt. Dette virker urealistisk da det ikke reflekterer reel drift og anses som en svakhet i modellresponsen.

Ut i fra analysene fremstår syntetisk treghet som et bedre alternativ enn roterende fasekompensator med tanke på kompensering for lav roterende masse. Dette skyldes lav treghetstidskonstant hos fasekompensatoren sammenlignet med den fleksible forsterkingen på syntetisk treghet. Da metoden er ny og forholdsvis lite utprøvd i praksis kreves mer studier, særlig for HVDC-kabler. I denne oppgaven ble vindmodellen også brukt for å demonstrere syntetisk treghet på HVDC-kabler. Dette er en forenkling som er mulig siden kun tilfeller med import er studert. Dessverre vil ikke dette gi helt korrekt respons for en HVDC-kabel, da vindmodellen er basert på vindturbinens mekanikk med å bremse for så å akselerere turbinen. Dette skaper et gjenopprettningsbehov av effekt som ikke er tilfelle for en HVDC-forbindelse, da kilden i "den andre enden" anses som ubegrenset. I Norge er vindplanene for fremtiden usikre. Regjeringen har et mål om 3000-3500 MW installert vindeffekt innen 2020, men dette er muligens for optimistisk. Derimot skal 2800 MW nye HVDC-forbindelser bygges og dette er derfor en mer realistisk kilde å satse på for å inkludere syntetisk treghet.

Hvorvidt FCR kravene vil sikre tilstrekkelig roterende masse er vanskelig å si fra analysene. Fem sekunders kravet i FCR-D virker relativt strengt fra disse simuleringene. Det krevde store mengder økt vannkraft tilkoblet for å tilfredsstille dette og dermed virker det sannsynelig at også de andre kravene oppfylles. Dette bør ikke anses som et resultat, da det kan skyldes en treg modellrespons. Oppbyggingen av FCR er et tema som vurderes hos systemoperatørene i dag. Fra analysene virker oppdelingen av FCR-N og FCR-D vanskelig å forholde seg til, samtidig som FCR-D kravene relatert til aktiveringsnivå på tid ikke henger sammen med totalt krav om frekvensrespons. Dette bør defineres klarere eller endres. I tillegg bør treghet inkluderes, enten som en del av FCR eller i et eget marked, da lav roterende masse i systemet er et faktum både for tidligere og fremtidige hendelser.

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IX. ABBREVIATIONS

AGC - Automatic generation control

DI - Dimensioning incident

FSC - Full scale converter

FCR - Frequency containment reserve

FRR-A - Automatic frequency restoration reserve

FRR-M - Manual frequency restoration reserve

HVDC - High voltage direct current

LFC - Load frequency control

POI - Point of interconnection

PSS - Power system stabilizer

p.u. - per unit

ROCOF – Rate of change of frequency

SC - Synchronous condenser

SNSP - System non-synchronous penetration

TSO - Transmission system operator

VSC - Voltage source converter

WT - Wind turbine

WTG - Wind turbine generator

1 INTRODUCTION

1.1 BACKGROUND AND OBJECTIVE

The characteristics of the Nordic power system are changing, and in the future the power system will face new and different challenges. As the expansion of the conventional large scale hydro has passed its peak, a new energy mix with an increasing amount of modern wind turbines and small scale hydro power is a growing trend in the Nordic countries. In addition, the nuclear power in Sweden is expected to be reduced during the years to come.

There will be more HVDC connections in the future. Today 2400 MW HVDC cables are connected from Norway to Denmark and the Netherlands. Within 2020, this number will be more than doubled when the new cables to Germany and Great Britain are finished, and the total HVDC capacity will be 5200 MW. HVDC cables separate synchronous areas and do not contribute to inertia or frequency response.

In total this means less rotating mass in our power system. Rotating power system components contribute to short circuit capacity, reactive power and inertia. The total system inertia in the Nordic power system is decreasing. Today there is no formal control of the amount of inertia available in the power system. The question is whether the future levels of inertia will become a problem.

The frequency quality in the Nordic power system has decreased during the later years. There are several reasons for this, including mismatch due to hourly trading hours in the markets and generation change, mismatch between production and consumption in the hours where consumption changes quickly, more fluctuating production, slow frequency oscillations and reduced levels of inertia.

A future scenario of concern is a summer day or night when load is low, HVDC import is high and production is light. Large hydro and nuclear units are off-line or out for maintenance, while wind power constitutes a large share of the total power production.

If the inertia of tomorrow's power system is low, how can this be compensated for in a successful way?

1.2 DEFINITIONS

The following definitions are relevant in this thesis:

- Modern wind turbines - wind turbines of variable speed that are electrically decoupled from the power grid through converters.
- Small scale hydro - hydro units with less than 10 MW production capacity and lower inertia.

1.3 SCOPE

The object of this thesis is to investigate volumes of inertia and FCR for several scenarios of interest. This will be done through simulations in PSS®E. In addition, methods for compensating low inertia will be discussed and tested in simulations. A theory part is included, in which theory of frequency response and mechanisms in the Nordic System are presented. Also compensation alternatives and their potential in Norway are briefly presented. Economic perspectives are not considered in this thesis.

1.4 METHODOLOGY

Dynamic analyses are conducted in PSS®E. A Nordic aggregated model consisting of 44 buses called Nordic44, is used for the simulations. The model is tuned according to a recent event in the Nordic System. Different scenarios are tested including a summer day from June 2013 and different versions of a future 2020 scenario with high import. The production portfolio of today is compared with Statnett's "worst case 2020" production share which includes significant amounts of wind power. Compensating alternatives are considered for these scenarios, including synchronous condensers, synthetic inertia on wind and synthetic inertia on HVDC cables.

1.5 OUTLINE

The report is outlined as follows: In chapter 2 a theoretic background on frequency response is presented. In chapter 3 the frequency controls in the Nordic system are explained. In chapter 4 the status of inertia in the power system is presented, for Norway and other countries. In chapter 5 it is given a brief introduction on possibilities on inertia compensation. In chapter 6 the modeling is described. In chapter 7 the simulation details and results are presented. In chapter 8 the results and assumptions are discussed. In chapter 9 the conclusion is presented and in chapter 10 further research areas are proposed. In the appendix, production, load and load flow data, as well as dynamic modeling and wind modeling are presented. Finally a simple system used for testing is shown in the appendix.

2 FREQUENCY STABILITY THEORY

2.1 POWER SYSTEM STABILITY

Power system stability is explained as the power system's ability to regain an equilibrium state after being subjected to a physical disturbance [1]. Three sections of stability are defined; rotor angle -, frequency - and voltage stability as shown in Figure 1. In this thesis, frequency stability is studied.

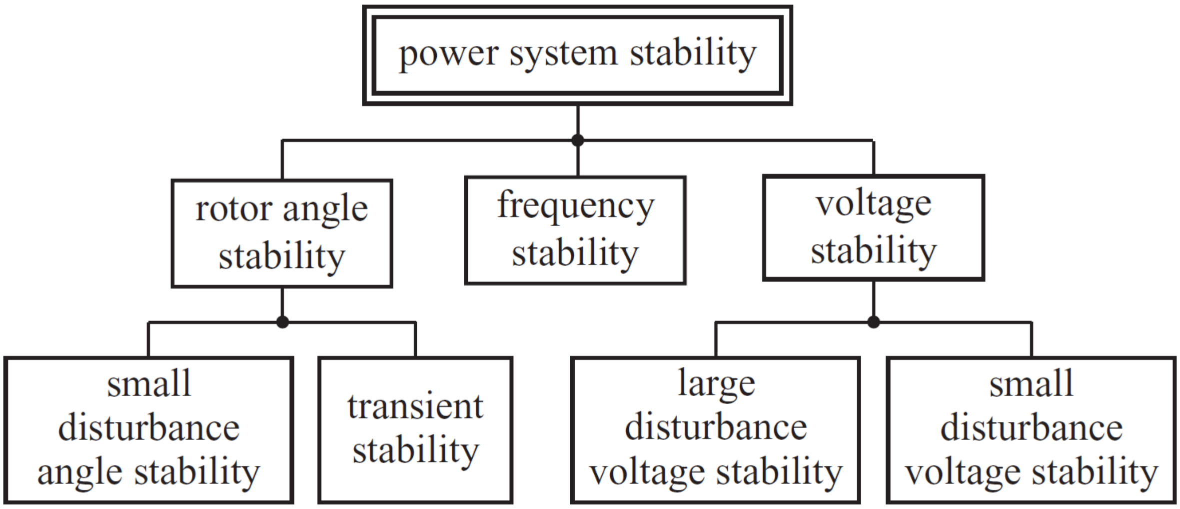

Figure 1: Classification of power system stability [1].

2.2 KINETIC ENERGY

The amount of kinetic energy present in a power system will influence both transient stability and frequency stability. The kinetic energy of a mass is given in joule [J] or watt-seconds [Ws]. It is expressed as

$$E_{kin} = \frac{1}{2} J \omega^2 \qquad \textbf{2-1}$$

where J is the moment of inertia and ω is the angular speed [2]. The amount of kinetic energy in a power system is related to the inertia constants of individual production units. A reduction of the kinetic energy will make the system less stable.

2.3 FREQUENCY STABILITY

If total generation matches total system load plus losses the frequency will be constant and this is referred to as the system's equilibrium [1]. For satisfying operation the frequency should remain nearly constant [3]. If there is an imbalance between the active power generation and the load there will be a change in the kinetic energy in the interconnected system, according to the equation below [4]

$$\frac{d}{dt}\left(\frac{1}{2} J \omega^2\right) = P_{prod} - P_{cons} \qquad \textbf{2-2}$$

Due to the relationship $\omega=2\pi f$ it will also lead to a frequency deviation. The frequency is the same throughout the system and hence a change in active power demand one place in the system will be seen everywhere in the system. The deviation could be small if it is caused by a small mismatch such as a random load fluctuation or of larger size if for example a large generator is lost. Depending on whether there is an excess or a deficient production relative to the load, there will be a positive or a negative deviation from the nominal frequency. The stored kinetic energy in the system's rotating masses is used to handle the imbalance, as this energy can be released and transferred as electrical energy to the power system. This will result in a change in frequency with a rate dependent on the size of the initial power mismatch and the total system inertia [3, 5-7].

2.3.1 *Swing Equation*

The swing equation is the basis for understanding frequency changes in the power system. This equation relates acceleration or deceleration of a synchronous generator and turbine due to imbalance between mechanical and electromagnetic torque. The equation can be seen in many forms and is developed from Newton's second law for rotation

$$J\frac{d\omega_m}{dt} + D_d\omega_m = \tau_t - \tau_e \qquad \textbf{2-3}$$

where J is the total moment of inertia of the turbine and generator rotor in kg-m^2, ω_m is the rotor shaft velocity in mechanical rad/sec, τ_t is the torque from the turbine in Nm, τ_e is the counteracting electromagnetic torque and D_d is the damping-torque coefficient in Nms. An unbalanced torque on the rotor will lead to acceleration or deceleration of the rotor.

Further, when introducing mechanical torque and using relationships for rotor velocity (full derivation is shown in [1, 5]) the following equation is obtained

$$J\frac{d^2\delta_m}{dt^2} + D_d\frac{d\delta_m}{dt} = \tau_m - \tau_e \qquad \textbf{2-4}$$

Using the fact that power is the product of angular velocity and torque, multiplying the equation by the rotor synchronous speed ω_{sm} and utilizing that during a disturbance $\omega_m \approx \omega_{sm}$ will give the following equation

$$J\omega_{sm}\frac{d^2\delta_m}{dt^2} + D_d\omega_{sm}\frac{d\delta_m}{dt} = P_m - P_e \qquad \textbf{2-5}$$

Introducing the damping coefficient $D_m = D_d\omega_d$ and the inertia constant H (seen in equation 2-17) into the equation, and replacing mechanical power angle and angular speed with electrical radians and electrical radians pr second gives

$$\frac{2HS_n}{\omega_s}\frac{d^2\delta}{dt^2} + D_m\frac{d\delta}{dt} = P_m - P_e \qquad \textbf{2-6}$$

Replacing the damping term with P_D, using the fact that $d\delta/dt=\Delta\omega$, $\Delta\omega = \omega - \omega_s$ and finally converting the equation into per unit the following is obtained

$$2H\frac{d\omega}{dt} = P_m - P_e - P_D \qquad \textbf{2-7}$$

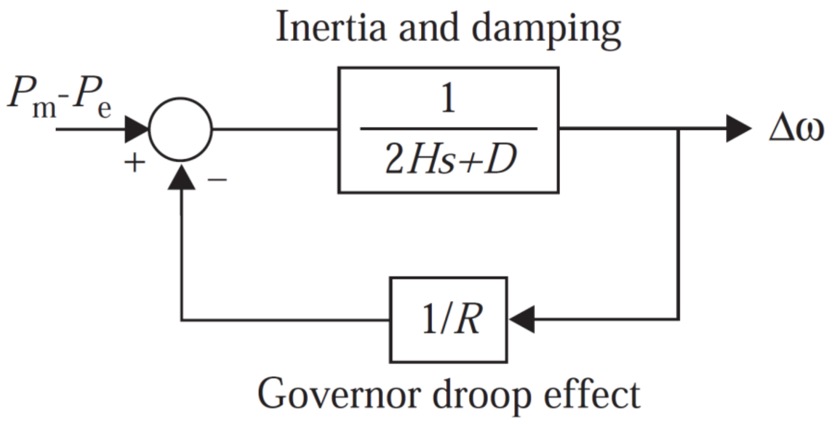

Figure 2: Illustration of the system dynamics, damping and governor droop [5].Note that the R in this particular figure represents the droop and corresponds to ρ, and not the R used later in this chapter.

A block diagram of the equation obtained with the droop included (see 2.3.2) can be seen Figure 2. The equation is now in the s-plane. Frequency is proportional to rotational speed, and a common form expressing the imbalance in power and change in frequency is shown below [8]

$$\frac{df}{dt} = f_n \frac{P_m - P_e}{2H} \qquad \textbf{2-8}$$

where f_n is the nominal system frequency in Hz, P_m and P_e is the mechanical and electrical power given in per unit. This df/dt is here given in Hz/sec and is also referred to as the rate of change of frequency (ROCOF). Notice that this form is a simplified version of the swing equation as the damping effect is assumed to be small.

2.3.2 *GENERATION CHARACTERISTICS AND DROOP*

In [1] it is shown that if the relationship between mechanical power and valve position is assumed a to be linear, the following holds for the ith generator

$$\frac{\Delta\omega}{\omega_n} = -\rho_i \frac{\Delta P_{mi}}{P_{ni}} \qquad \textbf{2-9}$$

where ρ_i is the droop for the ith generator, $P_{n,i}$ is the rated capacity of the unit i, $\Delta P_{m,i}$ is the additional output from the unit i due to the change in speed $\Delta\omega$ and ω_n is the rated speed. Since the rotational speed is proportional to frequency the following relationship also holds for the ith generator

$$\frac{\Delta f}{f_n} = -\rho_i \frac{\Delta P_{mi}}{P_{ni}}\,, \qquad \frac{\Delta P_{mi}}{P_{ni}} = -K_i \frac{\Delta f}{f_n} \qquad \textbf{2-10}$$

where $K_i = 1/\rho_i$. P_n is the rated capacity of the unit, f_n is the rated frequency and ΔP_m is the additional output from the frequency change Δf, all for unit i.

The droop (ρ) can be explained physically as the percentage change in speed required to move the valves from completely open to completely closed [1]. The droop is a parameter of the controller that may be adjusted [9]. From the equations above the formula for droop is

$$\rho = -\frac{\Delta f / f_n}{\Delta P_{/} P_n} \tag{2-11}$$

and the frequency bias, R is similarly defined as

$$R = \frac{\Delta P}{\Delta f} \left[\frac{MW}{Hz}\right] \tag{2-12}$$

For all generating units operating at the same frequency a similar relationship as in Equation 2-10 will hold for a sum of generators:

$$\Delta P_T = \sum_{i=1}^{N_G} \Delta P_{mi} = -\frac{\Delta f}{f_n} \sum_{i=1}^{N_G} K_i P_{ni} = -\Delta f \sum_{i=1}^{N_G} \frac{K_i P_{ni}}{f_n} \tag{2-13}$$

The generator characteristics of several units can be added up as shown in Figure 3. The graph shows how a system will compensate for a power imbalance with a deviation in frequency. When a large number of units make up one generator characteristic it is almost horizontal, this is beneficial as a large imbalance in power only will result in a small deviation in frequency.

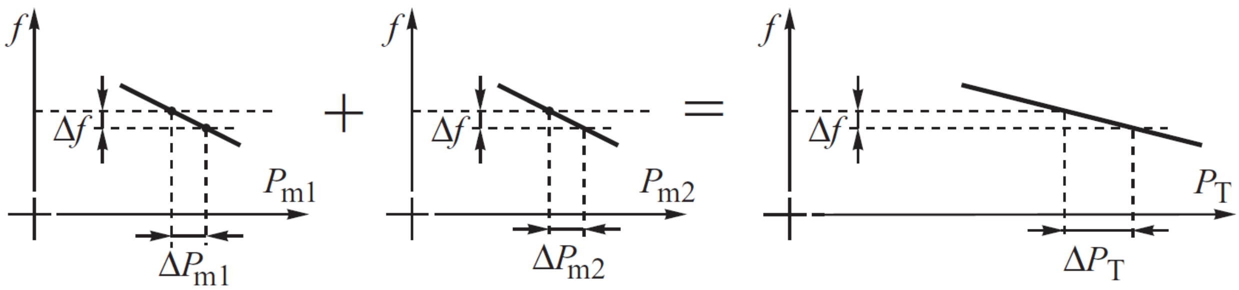

Figure 3: Generation characteristic for a sum of generators [1].

The characteristics above are assumed to be linear in the entire range of power output, but in reality they are limited by technical parameters. There will be a P_{Max} due to thermal and mechanical considerations. When operating at maximum output, a decrease in frequency will not be followed by an increased power output as $\rho=\infty$ (K=0).

In the figure above the individual generator characteristics are assumed equal. However, this is not always the case. If the spinning reserve is unevenly allocated between the generators, the equivalent generator characteristic will not be linear. This is the case for a real power system, where the characteristic is composed of many short sections with steeper slope as more generators reach their limits. Eventually, there will be no spinning reserve left and the characteristic will end as a vertical line [1].

2.3.3 *SPINNING RESERVE*

The spinning reserve is reserves that are actually spinning online. This will be the difference between the sum of power ratings and the sum of the actual load. If there is no spinning reserve online, there will be no regulating capacity available for frequency support following a disturbance. The amount of power the generators operate away from their P_{max} will therefore affect the generator characteristic [1].

2.3.4 *LOADS*

Loads are also dependent on frequency. The load will decrease if there is a drop in frequency as some type of loads draw less power if the velocity is reduced. A similar relationship holds for loads

$$\frac{\Delta P_L}{P_L} = K_L \frac{\Delta f}{f_n} \qquad \textbf{2-14}$$

where K_L is the frequency sensitivity coefficient of power demand. Generation response is more frequency dependent than load response, K_L=0.5-3 and $K_T \approx 20$ (ρ=0.05). Note the opposite sign; a decrease in frequency is associated with an increase in generation and a drop in load. The decrease ΔP_L is due to frequency sensitivity of demand, while the increase ΔP_T is due to turbine governors (primary control) [1].

The intersection between a load and generation characteristic will define the equilibrium point. The equation below explains how a change in total demand will cause an increase of generation by ΔP_T and a reduction in system demand by ΔP_L. Figure 4 depicts the same, where the equilibrium point will shift from 1 to 2 [1].

$$\Delta P_{demand} = \Delta P_T - \Delta P_L = -(K_T + K_L) P_L \frac{\Delta f}{f_n} \qquad \textbf{2-15}$$

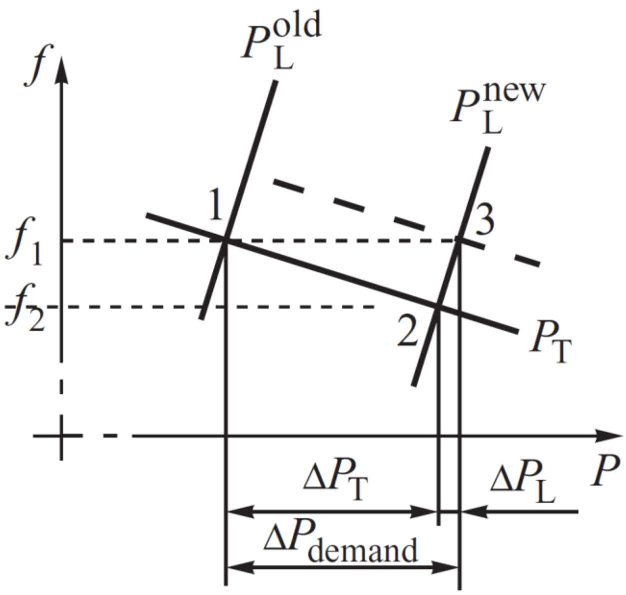

Figure 4: Equilibrium points for a change in power demand [1].

2.3.5 *DYNAMIC PHENOMENA DURING FREQUENCY RESPONSE*

What happens when a generator is lost is described through four stages in [1] on page 350-360, briefly summarized below. A simple system is used in the example; two generators at the same busbar that transfer power via a transmission line to an infinite busbar.

2.3.5.1 Stage I: Rotor swings in the generators - first few seconds.

If one generator is lost during parallel operation, the other unit will contribute to the production of the lost power. The sudden disconnection will produce large rotor swings in the neighboring unit and smaller rotor swings in generators in the rest of the system. For simplicity the rest of the system is neglected and thought of as an infinite busbar in this case. Because of the time scale, the generator transient model applies and the mechanical power supplied by the turbine remains constant. The equal area criterion can hence be applied. The disconnection has two effects; the equivalent system reactance will increase so the amplitude of the power-angle characteristics decreases. The power-angle characteristics are therefore

$$P_{-}(\delta_0) = \frac{E'V_s}{\frac{X_d' + X_T}{2} + X_s} \sin \delta_0', \qquad P_{+}(\delta_0) = \frac{E'V_s}{X_d' + X_T + X_s} \sin \delta_0' \qquad \textbf{2-16}$$

where P_- and P_+ means pre- and post disturbance. The generators are identical and represented by a transient emf $\underline{E}'$ behind an equivalent reactance that comprises the generator's transient reactance X'_d, the transformer reactance X'_T and the system reactance X_s. The second effect is that the mechanical power delivered will be reduced by half, meaning $P_{m+}=0.5P_{m-}$.

The left part of Figure 5 shows how the equal area criterion can be applied, showing the transient power-angle and the mechanical powers before and after the fault. Initially the plant operates at point 1 but as the rotor angle of the remaining generator cannot change immediately, the electrical power is greater than the mechanical power at point 2. Next the rotor loses kinetic energy (area 2-2'-4) as it is de-accelerated. Due to the momentum of the rotor its angle continues to decrease past point 4 until point 3. This is where the deceleration area (4-3-3') equals the acceleration area (2-2'-4). Finally, the subsequent oscillations are damped out and the rotor will operate at its new equilibrium point 4. The other part of the figure shows the lost generator power (ΔP_0) and the generating power of the remaining unit and the system (ΔP_r and ΔP_s). In [1] it is shown that the contribution of the remaining unit is proportional to the system equivalent reactance X_s, which is a measure of electrical distance between the system and the disturbance.

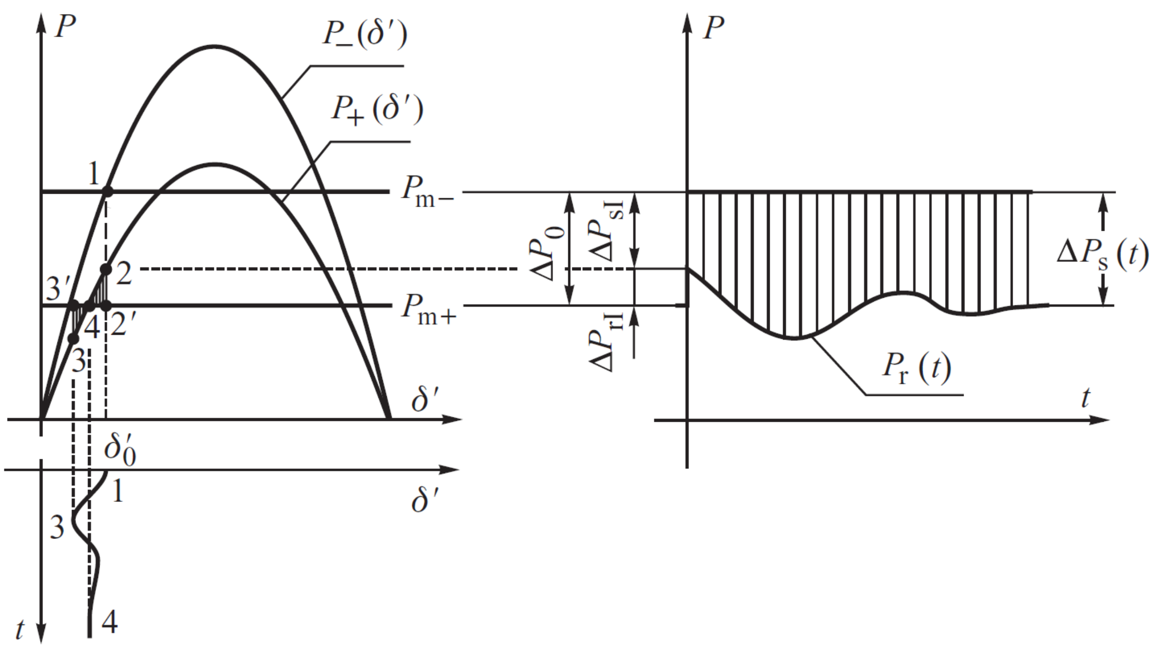

Figure 5: Stage I - Application of the equal area criterion [1].

2.3.5.2 Stage II: Frequency drop - a few seconds to several seconds.

The situation above will only last a few seconds before all generators in the system will slow down, and the system frequency will drop because of the power imbalance. At this stage only a generator's inertia affects the share of meeting the power imbalance among the generators, and not the electrical distance from the disturbance. After a few rotor swings in Stage I the generators will slow down at approximately the same rate (assuming all generators remain in synchronism). Each generator's contribution meeting the lost power depends on its inertia constant, as the contribution from a generator is decided from the ratio of the generator's own inertia and the inertia of the other generators.

2.3.5.3 Stage III: Primary control by the turbine governing system - several seconds.

This part depends on how the generators and loads react to the frequency drop. Operating frequency depends on the intersection of the P_T and P_L lines as described earlier. In Figure 6 this is shown as point 1 (this figure will be referred to throughout the description). After the disconnection of one generator the frequency initially remains the same, but the generation is shifted (point 2). Then the generation tends to move to a new intersection point for the two lines, however time constants of the turbines and their governors introduce a time delay and this intersection point cannot be reached immediately. The frequency now starts to drop as described in the two previous stages. In this third stage the turbine reacts to the drop in frequency and increases its power output, but the time delay in the turbine governor system causes the trajectory of the turbine power ($f(P_T)$) to lie below the static generation characteristic. As the frequency drops, the generated power increases and power taken by load decreases. A minimum of frequency is reached (point 3) when the difference between load and generation returns to zero. However, inherent inertia of the turbine regulator process will cause the mechanical power to increase further so that the generated power exceeds load power and the frequency will begin to rise. Again there is a point where the balance of power is zero, and this represents the maximum frequency (point 4) after the drop. The frequency oscillates further and reaches the steady state value of the frequency (III).

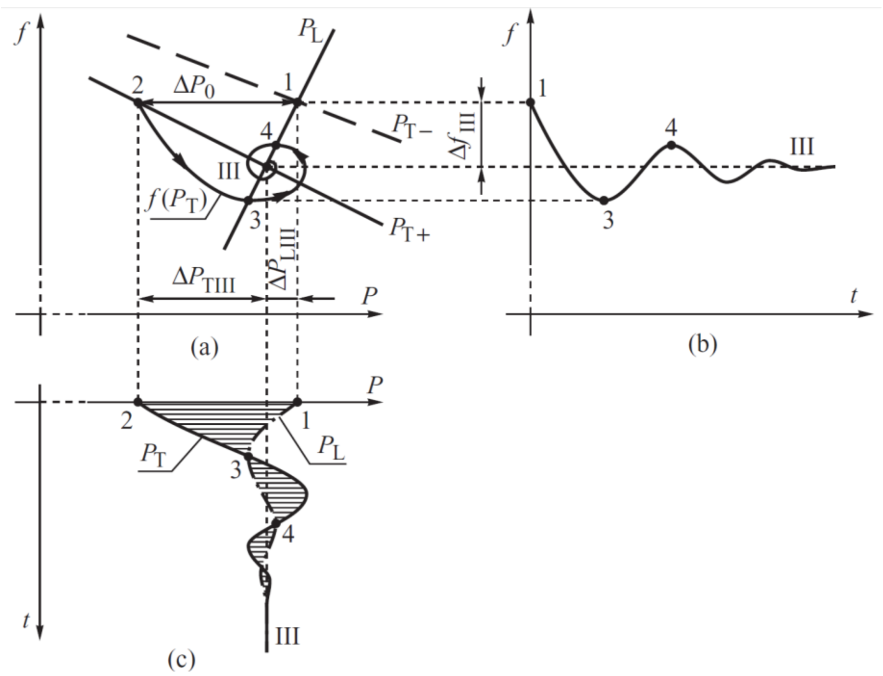

Figure 6: Stage III - a) generation characteristics, b) frequency changes, c) power changes.

2.3.5.4 Stage IV: Secondary control by the central regulators - seconds to minutes.

In this stage the frequency drop and deviation in tie-line power will activate the central automatic generation control (AGC) that is explained in 2.3.6.3. The purpose is to cover the remaining frequency imbalance and relieve the already activated reserves.

2.3.6 *FREQUENCY RESPONSE*

The frequency response indicates how production in a power system will change if the frequency in the same system changes and is given in MW/Hz. The response can be described as inertial response (fast primary response), governor response (slow primary response), automatic generation control (secondary control) and tertiary control. The inertial response dominates the initial frequency change in a frequency disturbance. After this a combination of system inertia and governor response determines the extreme value of the maximum or minimum frequency. Further the governor response and load response dominate the frequency mismatch until the AGC (see 2.3.6.3 for explanation) takes over. The tertiary control is slower and its task depends on the organizational structure. The timescale of the phases can be seen in Figure 7 and each phase is described in the following paragraphs [6, 8, 10].

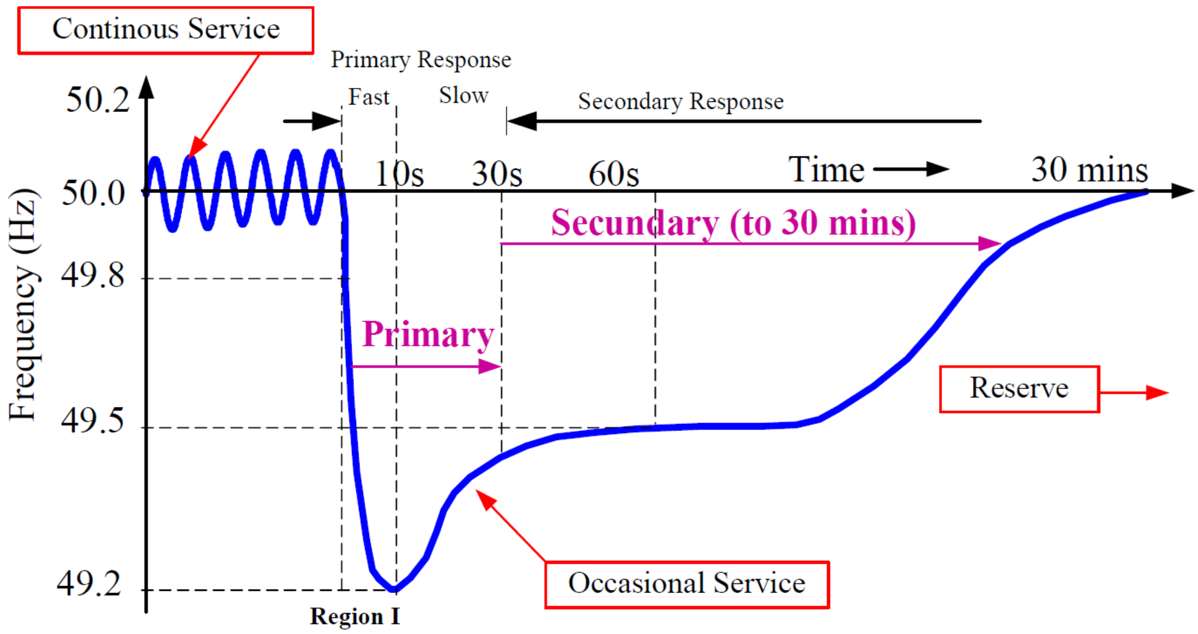

Figure 7: General frequency system response and controllers involved [8].

2.3.6.1 Inertia and inertial response

Inertia can be explained as the resistance to change in state of motion. In a power system the inertia is a measure of the energy stored in the rotating masses connected to the system and will prevent change in kinetic energy and hence frequency.

The inertia constant, H, is defined as the stored kinetic energy in mega joules at synchronous speed divided by the machine rating S_n in megavolt-amperes. H is given in the unit of seconds and “quantifies the kinetic energy of a rotor at synchronous speed in terms of the number of seconds it would take the generator to provide an equivalent amount of electrical energy when operating at power output equal to the MVA rating” [1]. H is given as

$$H = \frac{\frac{1}{2} J \omega_r^2}{S_r} \quad \textbf{2-17}$$

where J is the total moment of inertia in kg-m², ω_r is the rated mechanical speed in rad/sec and S_r is the base apparent power in MVA. In Figure 8 the effects of different inertia constants (and hence kinetic energy) can be seen in a frequency response. A small H gives a steeper and less damped response, while the responses with larger inertia constants are less steep and better damped.

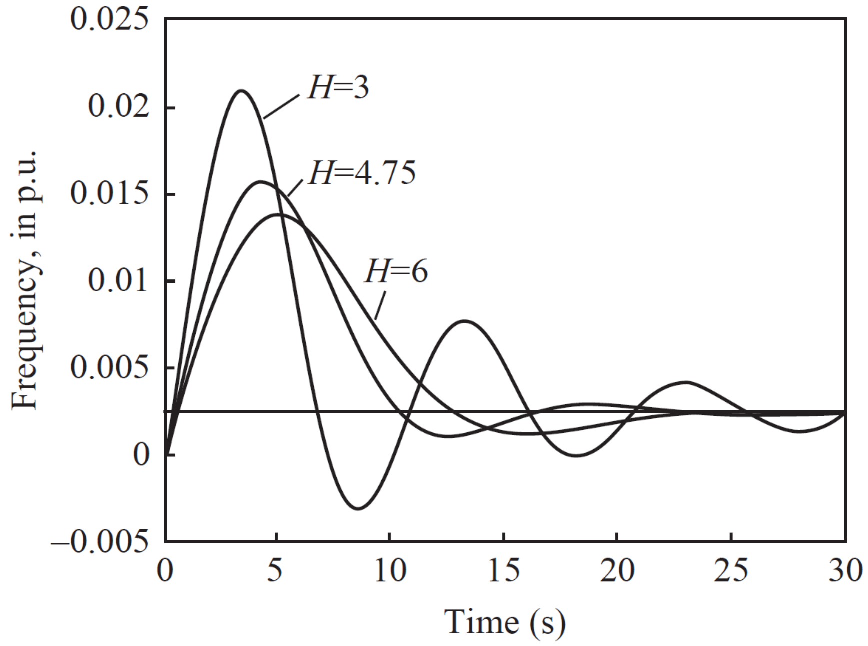

Figure 8: The effect of varying the inertia constant, H [5].

The mass of the rotating unit determines the inertia, heavier generators contribute to more inertia than lighter ones. The sum of all inertia of the spinning generation (and load) is referred to as the total system inertia. This decides how resistant the system is toward changes and hence how the system limits the frequency change following an imbalance in the power system.

The contribution of a single load or generator to system inertia is decided from the change in system frequency that causes a change in rotational speed and hence a change in kinetic energy. This change in kinetic energy fed or taken from the power system is called the inertial response and reflects the system's ability to withstand the frequency drop. The inertial response determines the frequency lapse during the first seconds and is sometimes referred to as the fast primary response. The size of the inertial reserve (amount of stored energy) will affect the frequency drop and hence the rate-of-change-of-frequency (ROCOF) as this affects the time the governors have to act and restore the frequency [6, 7].

The ROCOF is the frequency gradient shown in Figure 9. The amount of inertia also affects the lowest or highest point for the frequency drop or raise respectively. The lowest one is called the nadir as shown in point B in Figure 9. The same figure also shows the nadir time t_{min} that is the time it takes to reach the nadir, Δf_{max} which is the absolute frequency deviation from nominal frequency, Δf_{ss} that gives the steady state frequency deviation and f_{ss} showing the steady state frequency [11].

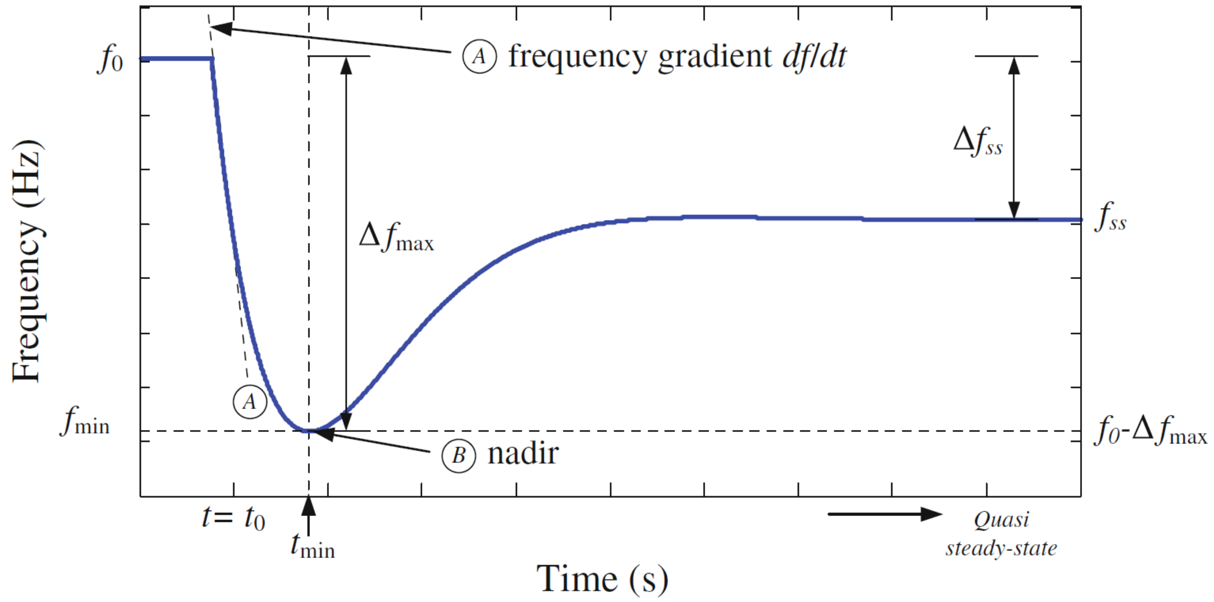

Figure 9: Primary frequency response showing main performance indicators [11].

The above mentioned factors are all measures that indicate the performance of the inertial and primary response. The magnitude of the maximum frequency deviation depends on several factors according to [11]:

- The frequency disturbance's amplitude and development over time.
- The kinetic energy of rotating machines in the system.
- Primary control and primary control reserve - how many generators contribute to the reserve and how is the reserve divided between these generators.
- The dynamic characteristics of the machines and loads.

2.3.6.2 Turbine governor and governor response

All generators have a source of mechanical power; this is called the prime mover and can be a steam turbine, diesel engine, gas turbine, water turbine or wind turbine. All prime movers behave similarly; as the power drawn from them increases, the speed in which they rotate decreases. Normally this decrease in speed is nonlinear; however governor mechanisms are included in order to make the decrease in speed linear with an increase in demand. The governor mechanism will provide a slight drooping characteristic when load is increasing and the turbine governor brings back the equilibrium between generation and load, but at a new level of frequency [12]. The generation characteristics and droop was explained in 2.3.2.

Hydro governors have the most persistent response to frequency deviations. Since nuclear governors are block loaded they will not respond to frequency and the sustained response of coal and gas is limited [5]. However, all these units contribute to the inertial response.

It is important to note that in practice the only considerable contributors to primary reserves and primary response in the Nordic countries are the hydro governors. The primary reserve is referred to as frequency containment reserve (FCR) in the grid codes explained in 3.1.

Figure 10 depicts a simple governor model with droop derived from the swing equation and the droop equation. The following parameters are used; inertia constant H=5s, damping D=0.8, governor droop = 5 % and time constants for turbine and governor valve as in the figure. A load step of 20 % has been applied and the 100 s simulated response can be seen in Figure 11, when assuming operation in an isolated system [5]. As can be seen the frequency returns to a new steady state level, leaving a Δf_{ss} to the AGC.

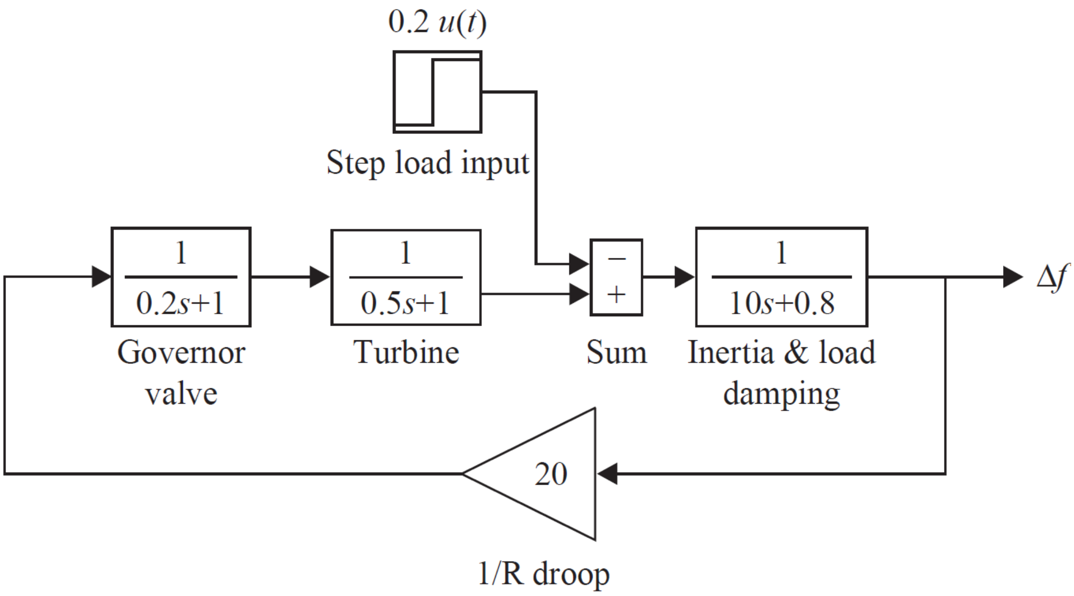

Figure 10: Simple governor droop model with droop in isolated operation [5]. (Note: R corresponds to ρ)

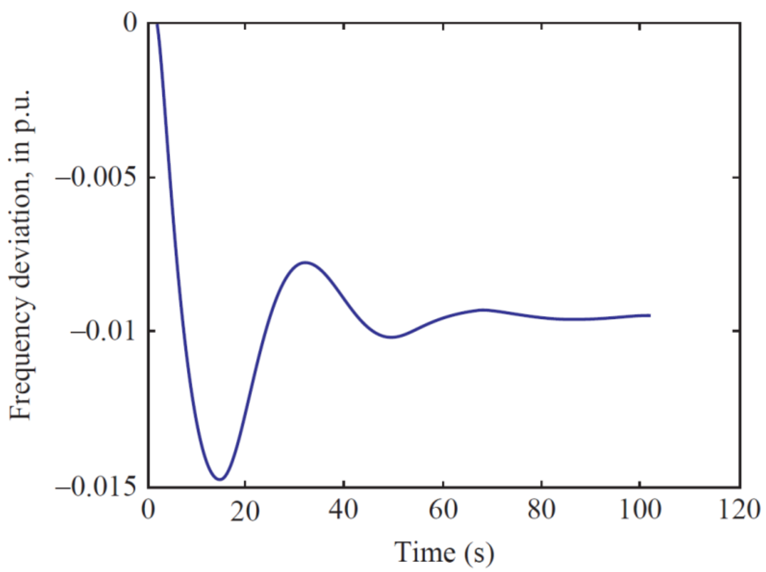

Figure 11: Frequency response of a governor droop model in isolated operation [5].

2.3.6.3 Automatic generation control (AGC)

Automatic generation control (AGC) of synchronous generators will change the mechanical power input to the shaft as a response to a frequency deviation from the set point value. A change in the P_{ref} setting in turbine governor system of individual generators will move the total characteristic upwards. This will bring back the nominal frequency at the required increased demand. This mechanism is not instantaneous.

AGC is referred to as FRR-A (automatic frequency restoration reserves) both in the Nordic system and in the new Network Codes from ENTSO-E. There is also a manual frequency restoration reserve (FRR-M). FRR is necessary if droop governors are present, as these will cause a permanent steady state deviation in frequency following a frequency drop.

Figure 12 is an extended version of Figure 10 and shows a block diagram for a simple AGC with a PI controller. This controller will bring the frequency back to its nominal value. The integral gain must be adjusted for optimal response [5]. The response is shown in Figure 13 and as seen the frequency now returns to the nominal value.

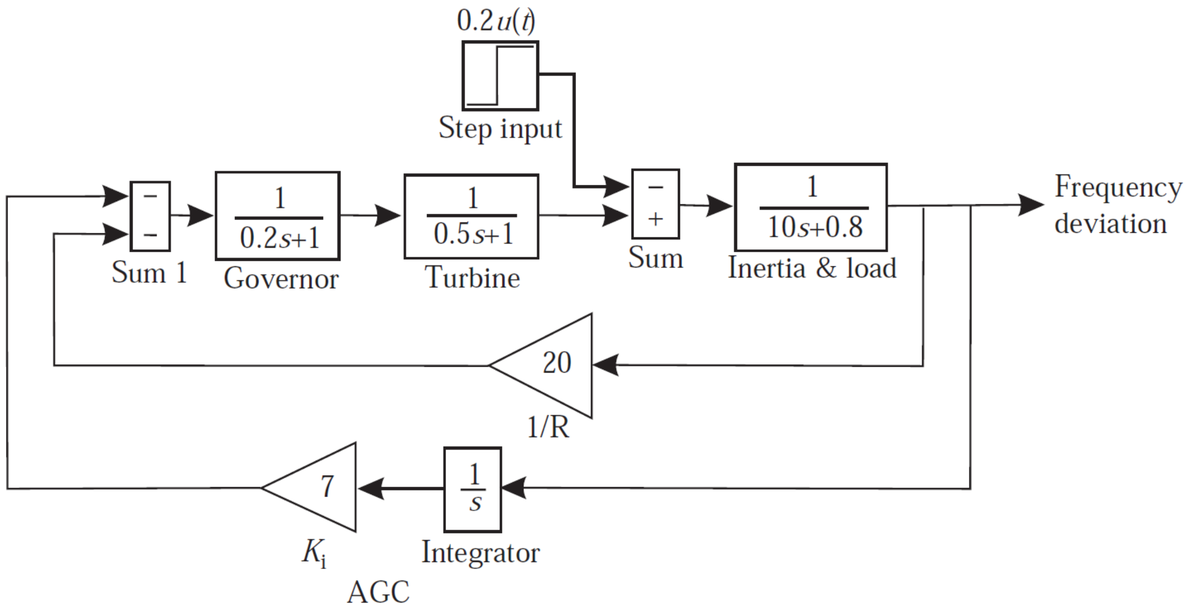

Figure 12: Block diagram of AGC for an isolated or single area system [5]. (Note: R corresponds to ρ).

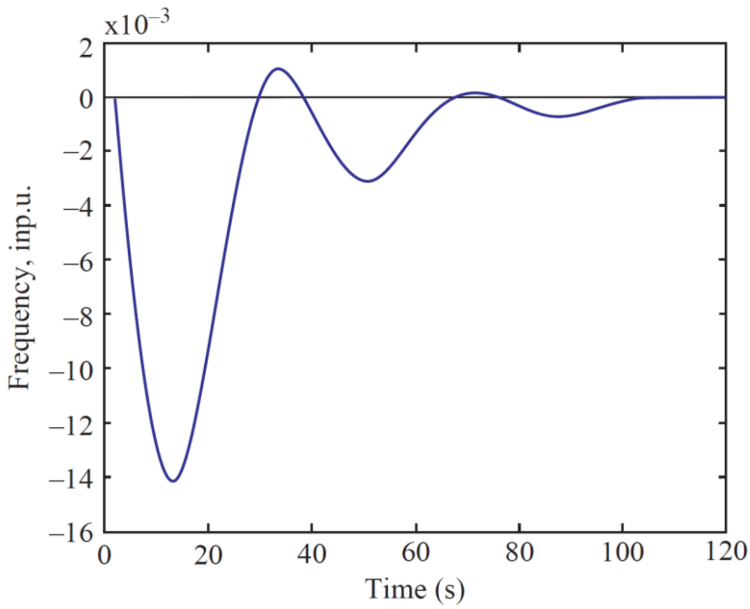

Figure 13: Frequency response of the AGC in an isolated or single area system [5].

3 ANCILLARY SERVICES

Ancillary services are "services that are fundamental for the quality of a power system". Measures of quality are security of supply, frequency stability, voltage level and voltage stability, in other words characteristics that are common for a number of consumers. Different power systems define different ancillary services, but normally reserves for balancing, reactive power and black start capability are included. System protection, grid losses and load following might also be included [9].

Frequency control is a part of the ancillary services. The frequency control is divided into three parts with different time horizons. They are all described below. The terms used are common for the Nordic as well as the European system operators as they are defined in grid codes from ENTSO-E.

3.1 FREQUENCY CONTAINMENT RESERVE (FCR)

The Frequency containment reserve (FCR) is the primary reserve. The aim is to manage imbalances instantaneously through automatic decentralized regulation of production [13]. For the Nordic system this reserve is further divided into FCR-N and FCR-D, where FCR-N is in use during normal operation, while FCR-D is used for disturbances. In order to ensure distribution of the reserves among the online units, the transmission system operator (TSO) requires that generators above 10 MVA can have a maximum of 12 % droop if they are not active in the market. During summer this requirement is lowered to a maximum of 6 % [14].

3.1.1 *FCR-N*

FCR-N is automatically activated when the frequency is in the area 49.9-50.1 Hz. The up/down regulating time for FCR-N is 2-3 minutes. The requirement of FCR-N is 600 MW in the Nordic system of which 210 MW is in Norway [13]. The division within the synchronous area between the subsystems is based on annual consumption, as seen Table 1. At least 2/3 of the frequency controlled normal operation reserve must be covered by the subsystem itself. This for potential splitting up and island operation [10]. The requirement of 600 MW should be available within +/- 0.1 Hz and this corresponds to a frequency response of 6000 MW/Hz. Since not all generators change their droop settings, Norway normally has about 400-600 MW FCR, but this value can be higher [15]. For FCR-N Statnett and Svenska Kraftnät solely use their hydropower, while Fingrid uses droop control on hydro and thermal in addition to the DC link to Russia [10].

	Annual consumption 2013 (TWh)	**Frequency controlled normal operation reserve (MW)**
Eastern Denmark	13.7	22
Finland	85.2	138
Norway	130.0	210
Sweden	142.5	230
Synchronous system	**371.4**	**600**

Table 1: Example of division of FCR-N for 2013 [10].

3.1.2 *FCR-D*

FCR-D is automatically activated when the frequency falls below 49.9 Hz. The reserve must be of such volume and composition that a dimensioning incident (DI) shall not cause a steady state frequency below 49.5 Hz. The requirement means that all the FCR-D must be activated prior to this level. The DI is defined as the largest generator outage the system is dimensioned to handle.

If frequency drops to 49.5 Hz the control should be 50 % activated within 5 seconds and be fully activated within 30 seconds. Location of FCR-D must be taken into account when transmission capacity is decided, as operation of FCR-D should not cause any other problems in the power system. As for the FCR-N, 2/3 of the FCR-D must be covered by the subsystem itself. Automatic and agreed load shedding can be a part of the FCR-D; this may for example be industrial, district heating and electric boiler consumption. The same applies for HVDC emergency power. The total FCR-D response is required to rise to a power level corresponding to the DI, minus 200 MW representing self regulation of load in the system. The DI in Norway is 1200 MW and the Norwegian part if the FCR-D is about 350 MW. From Table 2 it can be seen how the FCR-D requirements are obtained. For the Nordic system Sweden has the largest DI of 1400 MW, but this might increase to 1650 MW when the nuclear power plant in Finland, Olkiuoto 3 (OL3) gets online. The Norwegian DI will also increase to 1400 MW when the new HVDC cable Nordlink gets in operation in 2019. At Statnett, FCR-D consists of hydropower and HVDC emergency power. For Svenska Kraftnät FCR-D is made up of hydropower, HVDC emergency power and start up of gas turbines, while for Fingrid it consists of hydropower, thermal plants and sheddable load [10, 13, 14].

	Dimensioning faults (MW)	**Frequency controlled disturbance reserve (MW)**	**Frequency controlled disturbance reserve (%)**
Denmark	600	176.5	14.7
Finland	880	258.8	21.6
Norway	1200	352.9	29.4
Sweden	1400	411.8	34.3
Total		**1200**	**100.0**

Table 2: How requirements for FCR-D in the Nordic System are decided [10]. Example from week 13 in 2013

There are markets for primary reserves, including one weekly and one daily market. The weekly market runs before the Elspot market, while the daily market runs after the Elspot market to cover the remaining requirements after the trading in Elspot. Interchange with other TSO is also done at this point. This is to avoid comprehensive changes in planned production after market clearing and to ensure sufficient amount of reserves. FCR-N is offered in both markets, while FCR-D is only offered in the daily market. As mentioned all generators with a capacity above 10 MVA have requirements regarding the droop settings. These generators will get paid a given rate even though they are outside the marked. It is a national responsibility to procure sufficient primary reserves [13, 14].

The FCR-N and FCR-D frequency response can be seen in Figure 14. Note that the frequency response for FCR-D will vary, but today 3000 MW/Hz is the highest value that can be required in the range 49.9-49.5 [7].

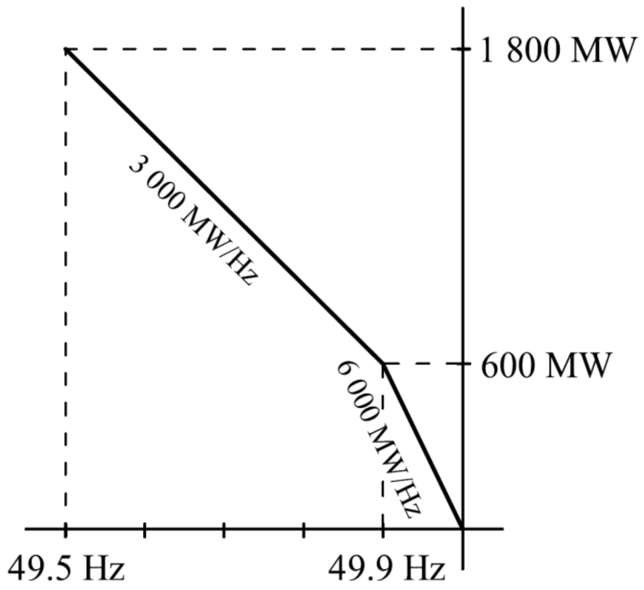

Figure 14: Frequency response for FCR-N and FCR-D [7].

3.2 AUTOMATIC FREQUENCY RESTORATION RESERVE (FRR-A)

The automatic frequency restoration reserve (FRR-A) is the secondary control and since 2013 this has been automatic in the Nordic system. The mechanism behind the FRR-A is the AGC explained in 2.3.6.3. The purpose of the secondary control is to bring the frequency back to 50 Hz, and release the primary reserve so this control will be ready to handle new deviations. The FRR-A will be activated by an automatic signal from the TSO to the supplier and production will change. When this signal is given the response time is between 120 and 210 seconds. FRR-A is also a market in weekly basis, prior to the primary control. The bids must be between 5 and 35 MW. Today the procurement is on national basis, but there is ongoing work for establishing a Nordic marked [13, 16].

3.3 MANUAL FREQUENCY RESTORATION RESERVE (FRR-M)

The manual frequency restoration reserve (FRR-M) is the tertiary control. This mainly consists of the regulation market (Regulerkraftmarkedet, RK) and the regulation option market (Regulerkraftopsjonmarked, RKOM). In Norway there is a requirement of 1200 MW for the dimensioning incident and 800 MW in addition to cope with bottlenecks and imbalances. There are different rules and practices across the Nordic countries. This reserve aims to release the primary and secondary reserves, as well as handling bottlenecks. There is a market used in merit order and the reserves must be activated within 15 minutes. The regulation market is a common Nordic balance marked where both producers and consumers can participate. The regulation option market is a Norwegian option market, mainly for the winter season. There are also bilateral agreements over longer terms for delivery of reserves [13].

3.4 OTHER FREQUENCY CONTROLLED SYSTEM PROTECTION ACTIONS

Figure 15 depicts other frequency controlled actions and their frequency level of activation. Three of these are briefly explained below.

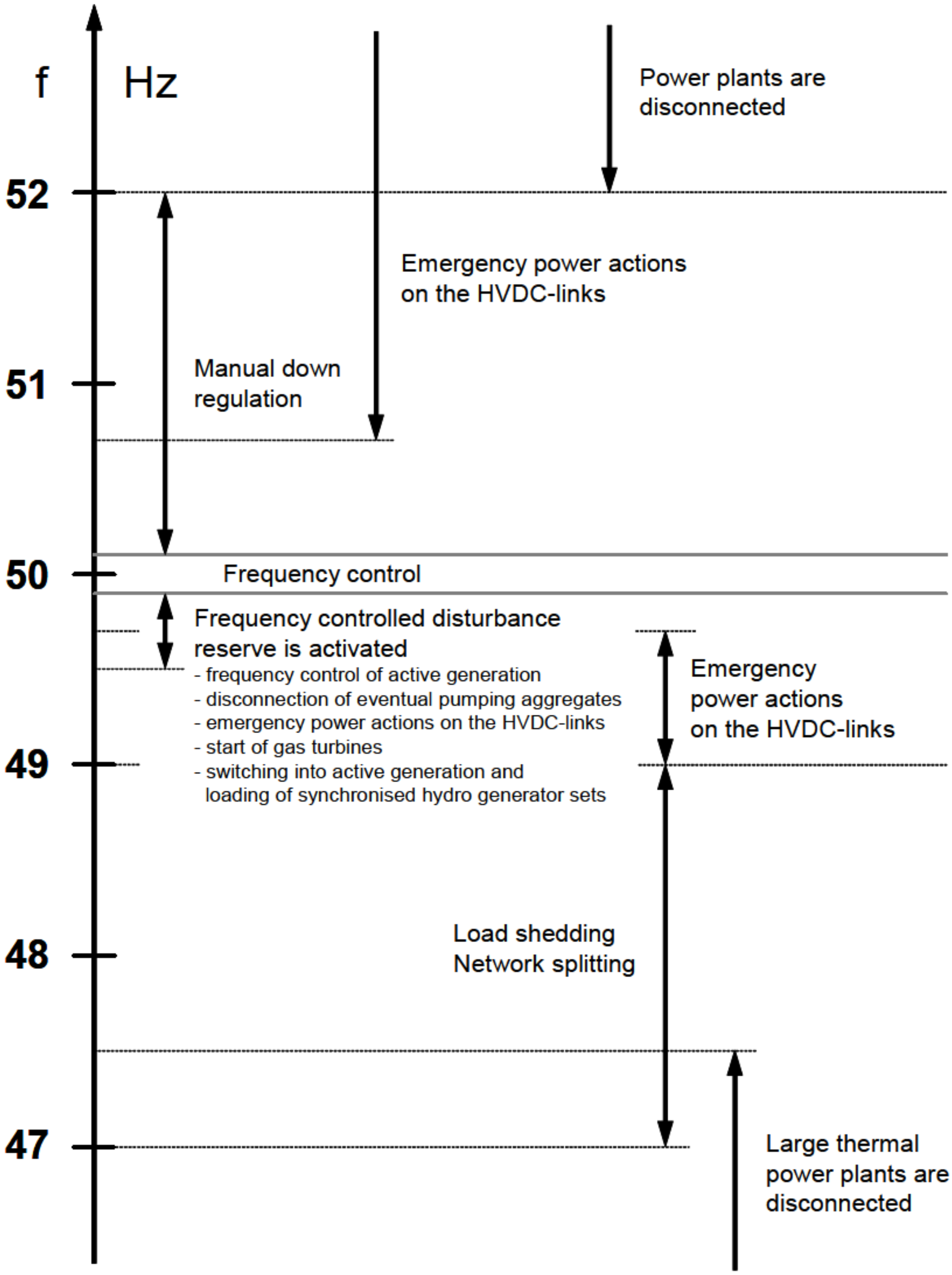

Figure 15: Frequency controlled actions in the previous Nordel system [17].

3.4.1 *Emergency power*

Emergency power is regulation of power on HVDC links. The control can be either automatic or manually on both sides of the links. Emergency power on HVDC links are available on all the traditional HVDC cables [10]. Figure 16 shows the principle of how it works for some of the cables in the Nordic System (the figure is from 2007 so all links are not depicted). As seen the emergency power are activated when the frequency is above or below a given level. The activation normally has a time delay of 100-500 ms [18].

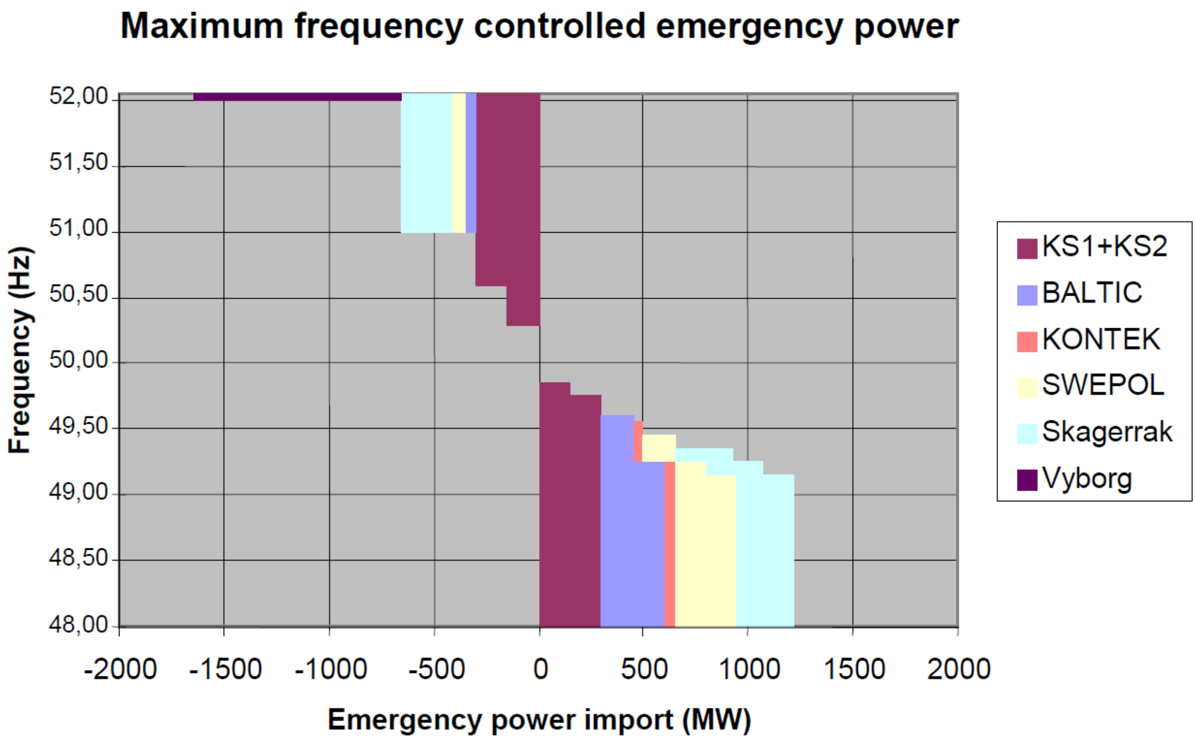

Figure 16: Frequency activated emergency power on HVDC cables in the Nordic System [17].

3.4.1 *Load Shedding*

Automatic load shedding will occur below 49 Hz. In Norway there is 7000 MW available for load shedding (during peak load). This will be activated in stages when the frequency is between 49.0-47.0 Hz. Fingrid has load shedding from 48.7-48.3 Hz and Svenska Kraftnät has load shedding between 48.8-48.0 Hz. Also manual load shedding is a system service during operational disturbances and power shortages. [10].

It is an ongoing discussion whether the limit for the transient frequency should be 49.0 Hz or 49.2 Hz to leave a margin to avoid triggering the load shedding during low frequency events [15].

3.4.2 *Start up of Production*

There is automatic frequency controlled start up of production both in Sweden and in Western Denmark. In Sweden a 700 MW gas turbine will start up in three stages of 0.1 Hz between 49.7 and 49.5 Hz.

4 INERTIA IN THE POWER SYSTEM

4.1 INERTIA REQUIREMENTS

4.1.1 *NORWAY*

Today inertia is not a part of the ancillary services in the Nordic system. There are no requirements regarding inertia in Norway. This has caused a growing concern over the last years, as low inertia levels will create challenges and might become a problem in the coming years. The frequency quality in the Nordic system has decreased during later years, inertia is pointed out as one of the reasons along with mismatch due to hourly trading hours and generation change, mismatch between production and consumption the hours where consumption change quickly, more fluctuating production and slow frequency oscillations [19].

4.1.2 *OTHER COUNTRIES*

In other countries the same applies. Requirements regarding primary frequency control are common, but when it comes to requirements for inertia things are different. Per 2011 no grid code had real tangible requirements, only loose indications (as seen in Table 3) and synthetic inertia was not reported as implemented on any commercial project [11, 20].

Country/state	Requirement	Comment
REE-Spain	No formal requirement	REE encourage development but does not foresee a need for this for the Spanish mainland for a long time
Hydro Quebec-Canada	Equivalent response as would have been provided by a synchronous machine with a inertia constant, H = 3.5 s	Basically undefined
Ercot-Texas USA	No formal requirement	Have been under discussion for a number of years
National Grid-UK	No formal requirement. A current draft suggests a primary control with +10 % over 5 s, and 1 s max delay time	NGET has been studying this for the last 2–3 years
Ireland	No formal requirement	Have been studied and so far been concluded not critical
Denmark	Similar to Hydro-Quebec	Same as for HQ
ENTSO-E Draft EU Grid code	The TSO shall have the right to require an equivalent delivery related to the rate of change of frequency.	Basically undefined

Table 3: Inertia requirements per 2011. Table taken from [11, 20].

The table shows different opinions about the inertia and how to define - and what to require from the synthetic inertia. Whether the requirements are effective today and how they are handled in practice is not known. As seen Ireland has no formal requirement; however, in the last years Ireland has, with one of the highest wind generation penetrations in Europe, had many inertia related studies. Ireland had 2211 MW installed wind capacity in the end of 2014 [21] and has ambitious targets of above 4000 MW installed wind within 2020, which will cover 37 % of system demand. A key conclusion is that frequency control will be one of the main challenges towards 2020. Analyses showed that the levels of synchronous inertia that will be available in 2020 will not be sufficient to meet system requirements. Even in 2010 1.2 % of total wind energy was dispatched down for security reasons, and this percentage is expected to increase with increased wind production. The reasons where either system wide (need for a minimum level of synchronous inertia and sufficient reserves both upwards and downwards) or local (avoid overloading of transmission lines and voltage control problems) [22]. During research a system non-synchronous penetration level has been defined in [23] as

$$SNSP = \frac{P_{wind} + P_{HVDC(import)}}{P_{load} + P_{HVDC(export)}} \tag{4-1}$$

where P_{wind} is the system wind power, P_{load} is the system demand and $P_{HVDC(import)}$ and $P_{HVDC(export)}$ are the power imported/exported through the HVDC interconnection.

Synthetic inertia and relaxing of the ROCOF settings (as these can worsen the initial frequency excursion) were the most effective in the simulations made in [23]. The same study also proposes other alternative operational strategies during high SNSP levels like;

- Make emergency power more instantaneous.
- Require a minimum amount of inertia online at all times (equivalent to nine 150 MW units with H equal to 4s).
- Leave a margin on wind production to allow for frequency response of governor type.

5 COMPENSATION FOR LOW INERTIA

Even though volumes of the FCR are satisfying, there are no measures for the total inertia available in the system. As explained in the introduction the volumes of inertia might be too low in the future power system, especially during summer. There are different alternatives to solve this; in this thesis three technical solutions for compensation have been given attention. These are synchronous condensers, synthetic inertia from wind turbines and synthetic inertia from VSC HVDC cables. Other possible operational alternatives include reducing DI when the power system is "operated light" or increasing the volume of FCR. An important question is whether it will be necessary to create own markets for inertia or if this can be included in the FCR-market or other existing markets.

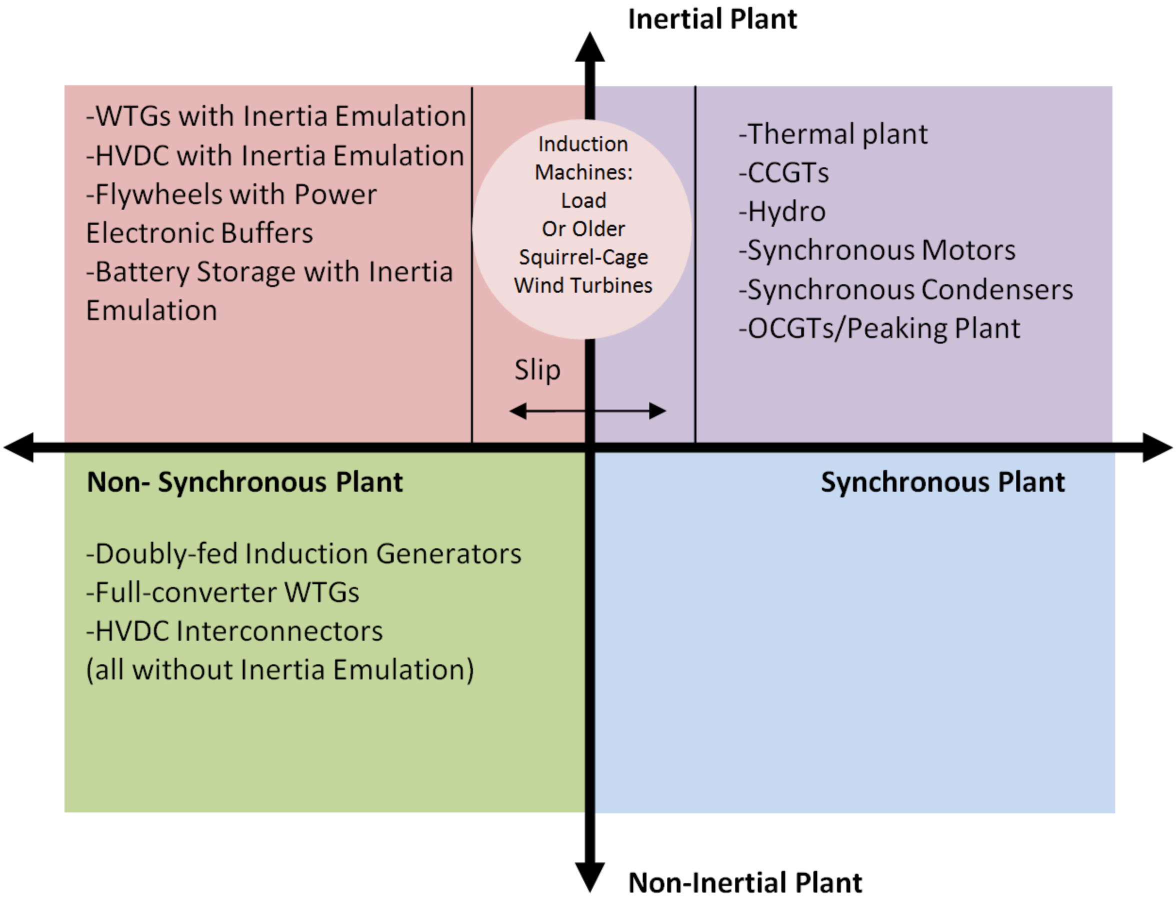

Figure 17: Classification of power generation based on inertia and synchronism [23].

5.1 SYNCHRONOUS CONDENSERS

A synchronous condenser (SC), also called synchronous capacitor or synchronous compensator, is a synchronous generator that operates without a prime mover or a synchronous motor run without any load. These are mainly used to improve voltage conditions, increase transfer capacities or deliver short circuit capacity during faults. The SC will inject reactive power into the grid, like an SVC. The rotating energy will as mentioned contribute to short circuit capacity, but it will also contribute to system inertia. Near HVDC installations the SC will reduce the chance of commutating faults in the rectifier [12, 24].

Using SCs is an old and conventional way to support the power system. However, the power electronics have developed and introduced static versions of reactive components like SVCs and STATCOMs. These where preferred instead of the SCs due to the reduced costs and less maintenance, as there are no rotating machinery. The interest in SCs has been low for the last twenty five years. Recently the increase in renewable generation has created a need for system support, and sometimes SCs are preferred instead of SVCs. As modern wind turbines cannot provide natural inertia support to the grid, a combination with SCs that will provide rotating inertia and give the grid increasing short circuit strength, will be beneficial [25].

5.1.1 *Synchronous condensers in Norway*

In Norway a synchronous condenser was built in Feda last year. This is where the NordNed HVDC cable is connected.

Other synchronous condensers in Norway can be seen in Table 4. Prior to the one built in Feda, no synchronous condensers have been built since 1982. This is most likely due to the reasons mentioned above.

Station	Rating [MVA]	Rpm	Voltage [kV]	Year built
Verdal	60	750	17	1971
Sylling	160	750	13	1975
Rød	55	1000	18	1975
Kristainsand	140	750	16	1977
Frogner	250	750	17	1978
Balsfjord	160	750	10.5	1982
Feda	170	-	15	2014

Table 4: Synchronous condensers in Norway. Data from [26] and Statnett [27].

5.2 Wind turbines with synthetic inertia

Wind turbines differ from many other power generators as they can only produce electricity in response to the resource immediately available, since it is impossible to store the wind. This means the output of a wind turbine is fluctuating and impossible to dispatch. The wind is utilized by the aerodynamic force of lift to produce a net positive torque on a rotating shaft that will produce mechanical power and further be transformed into electricity in a generator. The wind speed varies and this will affect the operation of the wind turbine [28].

The mechanical power possible to extract from the wind is given as

$$P = \frac{1}{2}\rho_{air}A_r v_w^3 C_p(\lambda, \theta) \quad \textbf{5-1}$$

where, ρ_{air} is the air density in kg/m^3, A_r is the area swept by the blades in m^2, v_w is the wind speed in m/sec and C_p is the power coefficient given as a function of λ and θ. λ is the tip speed ratio, the ratio between the speed of the tip of the blade and the wind speed; v_{tip}/v_w ($v_{tip=}\omega_{mech}$*r). θ is the pitch angle of the blades in degrees [28].

The traditional wind turbine was of fixed speed type, but with development of advanced power electronics the variable wind speed turbine has been introduced. This created another difference from the traditional power plants as these operate at almost constant rotational speed locked to system frequency, while for a modern wind turbine the speed is not synchronous with the grid, but is controlled to maximize production of active power [29]. The most common wind turbine is of variable speed type and either the doubly-fed-induction generator (DFIG) or the full scale converter (FSC) unit wind turbine.

The power electronic interface decouples the wind turbine from the power grid, thus the rotational speed is isolated from the system frequency. This means the WTs are producing constant power to the grid irrespectively of the system frequency, and the modern WTs do not contribute to the system inertial response and governor response. The modern wind turbines are adjusting the tip speed ratio and the pitch angle in order to operate as close as possible to the maximum output [6, 11, 29].

5.2.1 *SYNTHETIC INERTIA*

Due to the increasing level of wind power in the power system, the need for frequency support from WTs has been inherent. A lot of research has been done on the field referred to as synthetic, simulated, artificial or emulated inertia. It is possible for wind plant controls to provide a kind of inertial response (e.g. GE's WindINERTIA™ used later in this thesis). The aim of synthetic inertia control is to extract stored energy from the moving parts on the WT to produce incremental energy like that provided by a synchronous generator's inertia. This is done by including the ROCOF signal in the control loop [6, 19, 29].

In case of a large under frequency event, the inertial control can increase the power output of the wind turbine 5 to 10 % of rated power for several seconds. The increased power period is followed by a period of decreased power (recovery period) so the inertial response is energy neutral. If operated below rated conditions the stored kinetic energy from the turbine-generator rotor is temporarily transferred to the grid and returned later. If operated at higher wind speed the pitch control is used to increase the captured power and the steady state rating is exceeded temporarily. For the higher wind speeds the decline in rotor speed is smaller and the following energy recovery is reduced. Even though the control will try to imitate the response of a conventional synchronous machine there are some differences. It is important to note that this control is asymmetric and will not respond to high frequency events; however there is another functionality available for high frequency events. The control will only respond on larger events where the inertial response is crucial to avoid load shedding etc. and not to small frequency changes during normal operation [29]. The GE inertia model is explained in detail in 6.4.

Kinetic energy stored in a wind turbine's rotating parts is dependent on the mechanical turbine speed and mass. The additional power that can be released from a wind turbine's kinetic energy is dependent on the stored energy and the possible speed reduction. The change in rotor kinetic energy due to a decline in rotational speed from ω_0 to ω_1 ($\Delta\omega$) is

$$\Delta E = \frac{1}{2}J(\omega_0^2 - \omega_1^2) = \frac{1}{2}J(2\omega_0\Delta\omega + \Delta\omega^2) \qquad \textbf{5-2}$$

where J is the wind rotor inertia in kgm^2 and $\Delta\omega$ is the rotor speed change. The power released is estimated as

$$\Delta P = \frac{\Delta E}{\Delta t} \qquad \textbf{5-3}$$

hence the power output depends on initial speed, reduction in speed and duration of the speed drop [30].

As the control strategy of the inertial response includes additional power generation, a limiting factor is extra heat and stress on components. In this case the duration of the response is short so the thermal losses in generator windings are not high enough to be considered as a risk. Also the converters have approximately 10 % headroom due to their MVA ratings [30].

In [6, 11] the mentioned inertia emulation concept is called “releasing the hidden inertia”. The control can be seen in Figure 18 and is somewhat different from the one used for simulations later in this thesis. As the principle is the same, it is still relevant for background theory.

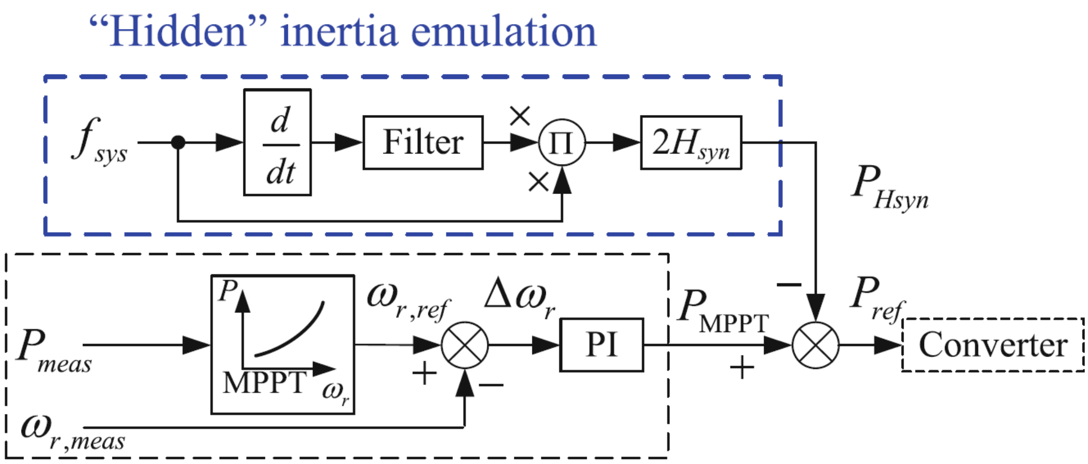

Figure 18: Hidden inertia controller [11].

The active (inertial) power ΔP achieved is

$$\Delta P_{H_{syn}} = 2H_{syn} x f_{sys} x \frac{df_{sys}}{dt} \quad \textbf{5-4}$$

where H is the synthetic inertia constant in seconds and f_{sys} is the system frequency in pu. The power electronic converters in the wind turbine make it possible to quickly store and release significant amounts of kinetic energy in the rotating masses because of the significant inertia and wide rotational speed possibilities [6, 11].

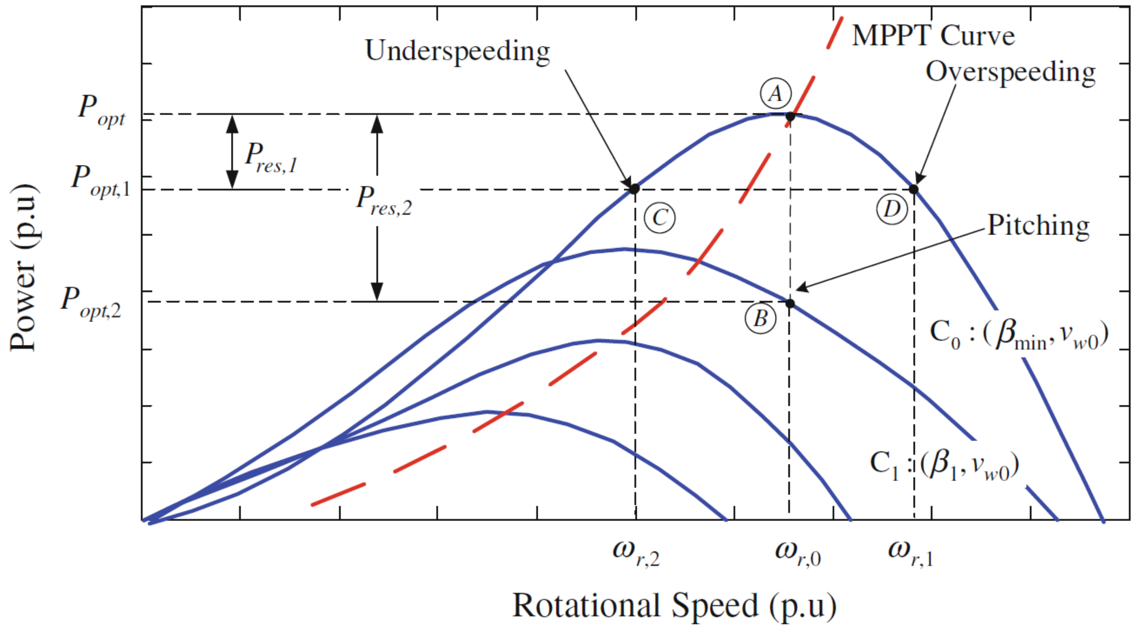

Figure 19: MPPT curve [11].

Another concept is regarding de-loading the wind turbine. Variable wind speed WTs are designed to operate at the maximum power point tracking (MPPT), meaning they have no power reserve to support the system frequency. This other concept uses a de-loader controller so that the WT do not operate at MPPT but over de-loading curves and saves additional available power as a reserve. This is done by using a pitch controller. A disadvantage of this strategy is a lower power output due to the change in operation point [6]. The MPPT curve can be seen in Figure 19. When moving the operational point from A to either C or D in the figure, the power output will decrease, yet the output can be increased if necessary. This strategy may be applied for FCR as well, as the increased power does not need to be temporarily. However, this is not tested in this thesis as the inertia compensation is the object.

Several studies show good results on the contribution of wind turbines to frequency response, GE's WindINERTIA is studied in [4] with good results. The second concept of de-loading is studied in [31, 32]. Some manufactures have integrated controllers on modern WTG to provide inertial response and these are commercial available; General Electric WindINERTIA™, ENERCON Inertia Emulation, Vestas etc. [8]. Even though the synthetic inertia only involves a control strategy, it is probably not possible to implement on existing wind parks due to strains imposed in the equipment. New turbines must be designed to withstand the strains [19].

5.2.2 *WIND POWER IN NORWAY*

In Norway the installed wind power capacity was 856 MW at the end of 2014. The production in 2014 was 2214 GWh or about 1.5 % of total production. There are 371 turbines installed with an average size of 2.3 MW. The utilization time in 2014 was 2701 hours of full load. In 2014, 45 MW of wind power was built at Raggovidda in Finmark and some old turbines in Mehuken in Sogn og Fjordane was changed [33]. The installed wind capacity can be seen in Figure 20.

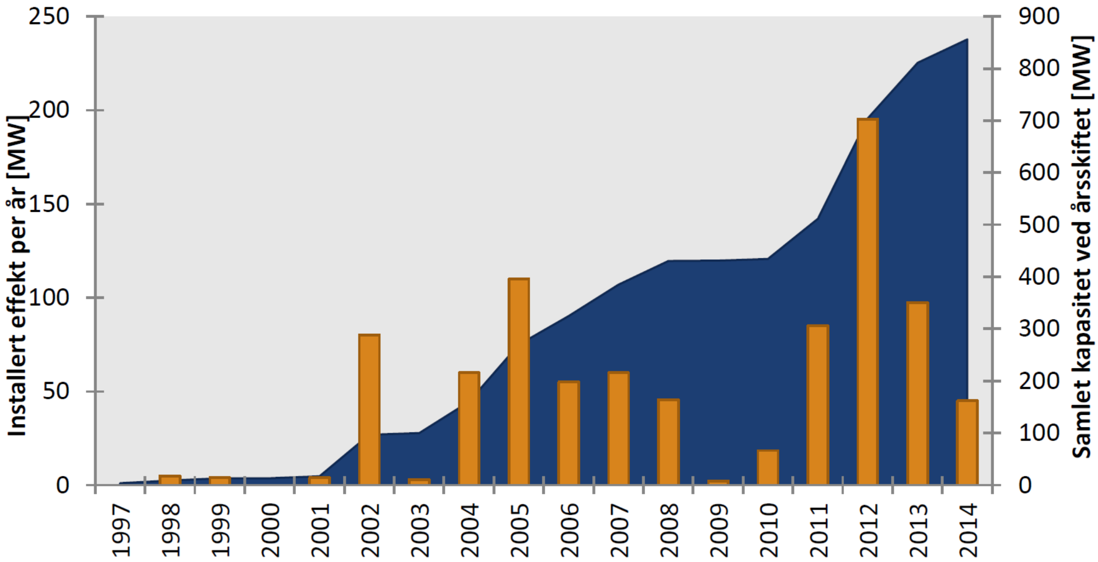

Figure 20: Installed wind power in Norway. Axes show installed capacity pr. year and graph shows total installed capacity [33].

As mentioned only new wind parks have the possibility to control synthetic inertia. As of today, 08.05.15, 20 822 GWh new production and 7452 MW new installed capacity have been granted license. In addition 12 218 GWh new production and 4132 MW new installed capacity have been applied for and are pending for licensing [34]. Figure 21 shows location of installed wind capacity and Figure 22 shows location of planned wind parks. Most wind capacity is located in NO3 (almost 50 %), followed by NO4 and NO2. The same areas dominate for the planned wind capacity.

Figure 21: Already installed wind parks in Norway. Small circle less than 10MW, medium circle 10-100 MW and largest circle above 100 MW [35].

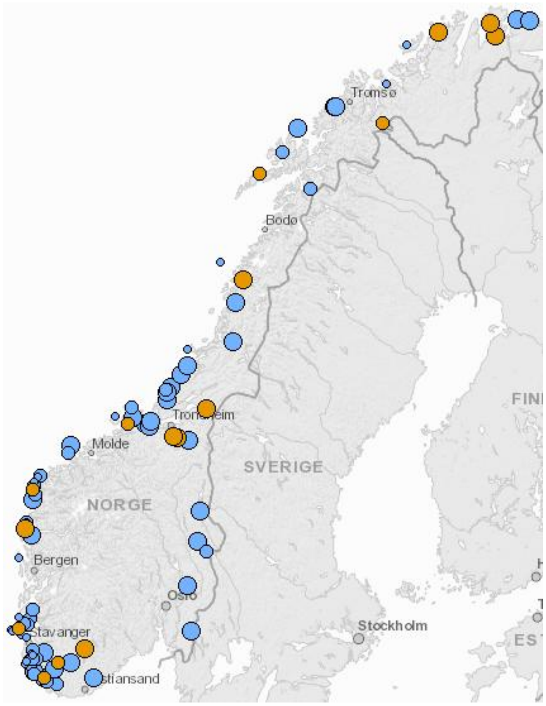

Figure 22: Planned wind parks in Norway. Light blue means granted license and orange symbolizes applied for license. Size of circles as the figure above [35].

In the market today no licensed wind parks are profitable without some kind of subsidies or governmental support, this even though wind power is a relatively mature technology. There are different kinds of financial support. Earlier Norway had an investment support system through Enova and all Norwegian commercial wind parks built earlier received 20-40 % investment support from Enova.

In 2012 Sweden and Norway agreed upon a common certificate system with a goal of total 26.4 TWh new renewable generation within 2020 and an obligation to finance half each. This system is market based and neutral regarding technology. Norway and Sweden will build nearly 13.2 TWh each, shared approximately equal between small scale hydro and wind for Norway and between bio and wind for Sweden. Sweden introduced a certificate system back in 2001 and today they have over four times more installed wind capacity than Norway [36].

According to Figure 20 there has been a decline in new wind capacity built in Norway. This is mainly of economic reasons due to low electricity prices, high investment costs and restrictions on grid capacity. According to [37] the government's plan is 3000-3500 MW installed wind capacity in Norway within 2020 which means 6-8 TWh. The green certificates are now extended by one year in Norway, to 2021 [38]. The largest power producer in Norway, Statkraft, recently decided not to invest in the planned wind parks in Trøndelag of a total 1000 MW. This decision reduces the likelihood that the government reaches their target. The low electricity prices and low prices on the electricity certificates are blamed for the projects not to be profitable [39].

5.2.3 *Wind power in Sweden and Finland*

Sweden had a total of 5424.8 MW installed wind power capacity at the end of 2014. The total production was 11.5 TWh or about 8 % of total power production [40]. SE3 has most of the installed wind capacity, followed by SE4 and SE2 [41]. Finland had 627 MW of installed wind power in the end of 2014. The production was about 1 TWh, which means about 1.3 % of their consumption [42].

In Sweden there has been an ambitious goal of a total of 30 TWh wind production in 2020, whereof 20 TWh is onshore and 10 TWh is offshore. Finland aims at 6 TWh wind production per year (2500 MW installed capacity) in 2020 [43].

Note that wind on Zealand (Denmark) is also a part of the Nordic system and increases the share of wind power. In the model used in this thesis Zealand is not included, and this is therefore not given any further attention.

5.3 HVDC Cables

High voltage direct current (HVDC) transmission system is a well known technology for transmission of bulk power across long distances. This is due to less overall costs and lower losses compared to AC transmission. The power converter is the core component and represents the interface with the AC grid. The AC/DC or DC/AC conversion is achieved through controllable electronic switches (valves) in a 3-phase bridge configuration [44]. The HVDC transmission systems can be divided into two categories;

5.3.1 *Classical HVDC*

In the traditional HVDC facilities thyristors are used in conversion from AC to DC and opposite. These are called LCC HVDC (Line Commutated Converter) or CSC HVDC (Current source converters). Thyristors are semi controllable, namely only controllable for the turn on possibility. There are several disadvantages with this rather mature technology; one is the need to provide commutating voltage for the thyristor, which means a generator or synchronous condenser is required on the inverter side. Also a capacitor bank is required to compensate for consumption of reactive power on both the rectifier and the inverter side. Another problem is low-order harmonics, hence large filters are necessary for removing these [44]. As mentioned, classic HVDC can contribute to the frequency response as HVDC emergency power.

5.3.2 *VSC HVDC*

Limitations of LCC/CSC HVDC are introducing Voltage Source Converter (VSC) HVDC as a replacing technology. This technology is often referred to as HVDC Light or HVDC Plus by ABB and Siemens respectively. This is a newer technology where the design is based on voltage source converters (VSCs). Transistors are used, normally Insulated Gate Bipolar Transistors (IGBTs), and operated with pulse width modulation (PWM). The converters are bidirectional, fully controllable (with turn-off possibility) and self commutating so there is no need for commutating voltage on the converter load side. An advantage with the VSC HVDC is that active and reactive power can be controlled independently; hence it is possible to maintain voltage and frequency stable. In addition supply of weak or passive grids and black-start capability are important features [45-47]. A single line diagram of the VSC HVDC is shown in Figure 23.

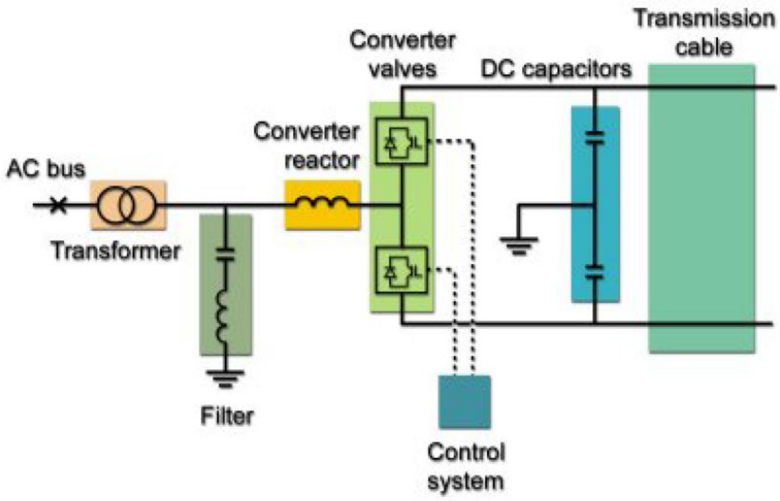

Figure 23: VSC HVDC single line diagram [47].

5.3.3 *Synthetic inertia on HVDC Cables*

The VSCs make it possible to create an inertial response on the VSC HVDC cables by controlling the active power. The principle will be the same whether it is another synchronous system or a wind farm on the other side, as long as there are two separated systems and active power is available. The topic is relatively novel meaning not much literature is found. However, ABB has implemented the functionality of artificial inertia in the Caprivi Link project in southern Africa between Namibia and Zambia [48]. In [48, 49] this feature is shown to work successfully by controlling active power in response to a frequency event.

There is some uncertainty regarding how the converter mechanism will work and several outcomes are possible. The findings in a previous M.Sc. Thesis [50] suggest that "converter A" senses the frequency deviation in grid A and reduces the DC-voltage. "Converter B" senses the reduced voltage and reduces frequency to get a frequency response in the grid at B. In the mentioned work the connecting end was a wind farm.

The active power must come from a source or another system. In this thesis the other end of interest is the connecting country. How this will work in practice is rather unclear yet. What is established is the need to deliver or receive instantaneous amounts of active power.

5.3.4 *HVDC CABLES IN NORWAY*

Two new HVDC cables will be built in Norway over the coming years; NSN between Kvilldal and the UK and NordLink between Tonstad and Germany. Both cables have a capacity of 1400 MW and are planned to be finished in 2020 and 2019 respectively. The technology for these cables will be VSC HVDC. The inclusion of these new cables will, as mentioned, increase the DI in Norway.

In addition there are already existing cables between Feda and the Netherlands (NorNed) and between Kristiansand and Denmark (Skagerak 1-4). Skagerak 4 came in operation at the end of 2014, with a capacity of 700 MW. This cable also uses the VSC HVDC technology. Skagerak 1-3 have a total capacity of 1000 MW and are using the classic HVDC technology. NorNed has a capacity of 700 MW and also uses the classic HVDC technology [51, 52]. Table 5 summarizes the details. Note that there are also existing HVDC connections to several offshore platforms not mentioned here.

Cable/connection	Between	Capacity [MW]	Technology
Nordned	NO-NL	700	Classical HVDC
Skagerak 1-3	NO-DK1	1000	Classical HVDC
Skagerak 4	NO-DK1	700	VSC HVDC
Nordlink (2019)	*NO-GE*	*1400*	*VSC HVDC*
NSN (2020)	*NO-GB*	*1400*	*VSC HVDC*

Table 5: Existing and planned HVDC connections Norway [53, 54].

5.3.5 *HVDC CABLES IN THE OTHER NORDIC COUNTRIES*

Sweden has several HVDC connections. Kontiskan goes to Jutland in Denmark and has a capacity of 300 MW+250 MW. The Baltic cable with a capacity of 600 MW goes through the Baltic Sea from Sweden to Germany. To Polen the SwePol cable of 600 MW is connected and to Finland the FennoScan cable with a capacity of 500 + 800 MW is connected. In addition, NordBalt (also called SwedLit) is under construction between Sweden and Lithuania with a capacity of 700 MW. Finland has a 1000 MW HVDC connection to Estland via Estlink1 and Estlink 2 with a capacity of 350 MW and 650 MW respectively. From Zealand in Denmark to Germany the cable Kontek of 600 MW is strengthening the interconnection to the continent [53, 54]. Table 6 summarizes the details. Note that there are also HVDC cables internally in Sweden and Finland. Figure 24 shows interconnections between the Nordic countries.

Cable/connection	Between	Capacity [MW]	Technology
KontiSkan	SE-DK1	550	Classical HVDC
Kontek	DK2-GE	600	Classical HVDC
SwedPol	SE-PO	600	Classical HVDC
Baltic	SE-GE	600	Classical HVDC
FennoScan	SE-FI/FI-SE	1300	Classical HVDC
EstLink 1 & 2	FI-EE	1000	VSC / Classical HVDC
NordBalt (Late 2015)	*SW-LI*	*700*	*VSC HVDC*

Table 6: Existing and planned HVDC connections rest of the Nordic system [53, 54].

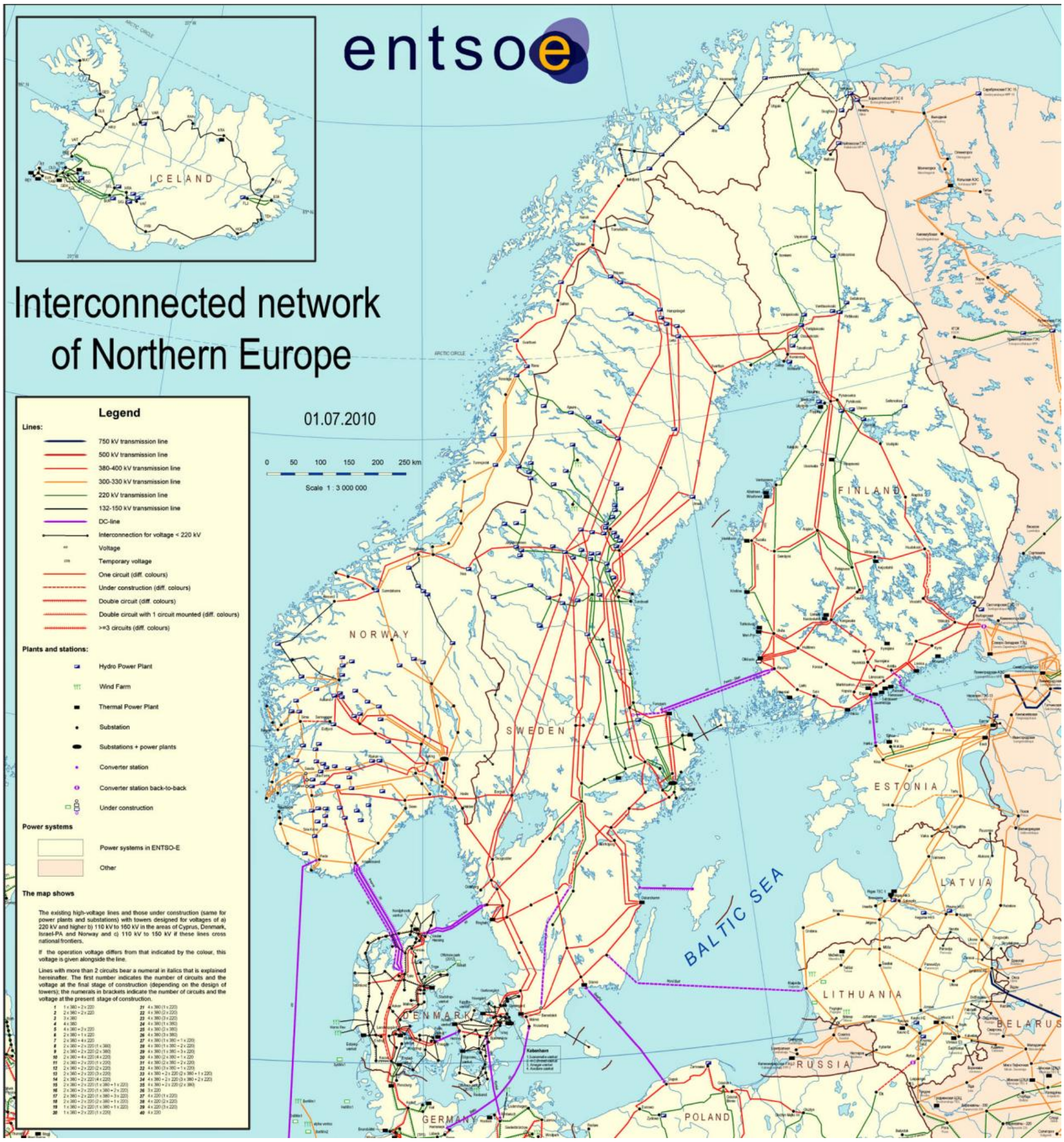

Figure 24: The interconnected Nordic System [55].

6 MODELING IN PSS®E

6.1 PSS®E

The simulation software used in this thesis is PSS®E. The focus is frequency stability and both load flow - and dynamic analyses will be conducted.

6.2 THE SYSTEM - NORDIC44

The system used in this thesis is the Nordic 44 model, seen in Figure 30. It comprises Norway, Sweden and Finland. As DK2 (Zealand) not is included in the model, production data from DK2 is not considered. The model is based on earlier Nordic models, but includes a more characteristic representation of the Norwegian part of the grid. Another change is that it includes several units instead of just one aggregated unit per bus, but it is still an aggregated model.

Originally the system includes 44 buses, 43 loads and 61 generators, whereas 12 generators in Finland, 20 in Norway and 29 in Sweden. All generator dynamic models are “GENSAL” and “GENROU” representing the dominating hydro and the nuclear/other thermal respectively. No wind was initially modeled. The swing bus is located in Sweden, at bus 3300.

The system is divided into eight areas in Norway, four in Sweden and two in Finland. As no information behind the model areas was given from the creators of the model the areas were distributed as best possible. Table 7 shows how the Norwegian model areas are translated into the Elspot areas. In southern Norway the division is rather unclear related to Elspot NO2 and NO5, as the partition is very different from the Elspot areas. However, the distribution in the table was assumed and followed throughout the thesis. The areas in Sweden principally correspond to the Elspot areas but in SE1 and SE2 the generators and loads are unevenly divided. Originally SE2 was only represented by one load and one small generator. To mend this, a change was made so generators 31xx correspond to SE1 and similar 32xx corresponds to SE2.

Elspot area	Nordic44 area
NO1	NO1 + NO6
NO2 + NO5	NO2 + NO3 + NO4 + NO5
NO3	NO7
NO4	NO8

Table 7: Norwegian Elspot areas and the corresponding areas in the Nordic44 model.

All HVDC cables in the original model are modeled as loads. This can be done since a negative load number will represent import.

Cable/connection	Between	Capacity [MW]	Corresponds to bus
Nordned	NO-NL	700	5620
Skagerak 1-3	NO-DK1	1000	5610
Skagerak 4	NO-DK1	700	Initially not modeled, included in the above bus for Scenario1.
KontiSkan	SE-DK1	550	3360
To Zealand(DK2)	*SE-DK2*	-	*8600*
SwedPol + Baltic	SE-POL+ SE-DE	600 + 600	8700
FennoScan	SE-FI/FI-SE	1300	3020/7010
EstLink 1 & 2	FI-EE	1000	7020
To Russia	*FI-RU*	-	*Included in bus 7020*

Table 8: HVDC cables and connections included in the Nordic44 model.

As seen in the Table 8 the connections from SE4 to DK2 and FI to RU is assumed included as loads in this model, even though they are not HVDC connections.

The connections between NO-FI and NO-RU are omitted from the model and hence ignored in this thesis. The flows on these lines are negligible so this will not create much difference. Also there is one line missing between NO4 and SE2 in the model assuming the original areas. As mentioned above the northern part of Sweden might be wrongly represented in the model and this might be the reason why one line is missing. Anyway, the line is not added for these simulations. This might make the transmission capacity between Sweden and Norway too small in the north.

6.2.1 *HYDRO GOVERNOR*

The hydro governor model used in this system is the classic PSS®E model "HYGOV" showed in Figure 25. This is a conventional way to represent a hydro governor and it works well in most cases. Today modern governors are electronic and represented by a PID or a PI controller.

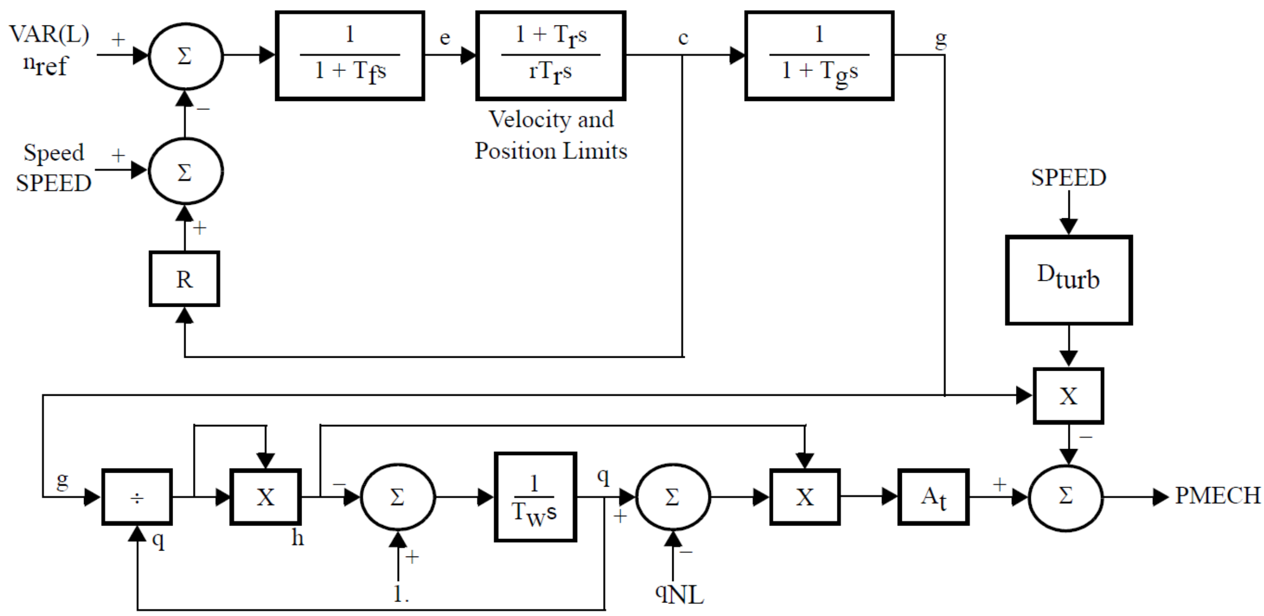

Figure 25: HYGOV - hydraulic and governor models [56].

The left upper part in Figure 25 represents the governor, and the parameters are given in Table 9. Most attention has been given to the three first parameters in the table. In the figure the parameter R represent the permanent droop, but as ρ is used in the theory part, $\rho_{PSS/E}$ will be used for this parameter instead of R. This parameter will decide a unit's power contribution under a frequency deviation and is therefore crucial for the steady state frequency. The temporary or transient droop r is affecting the transient part of the response and will regulate the change in frequency following a power imbalance. T_r is the governor time constant and will affect the time/slope from the frequency nadir to the restoration. See figures in 6.2.1.1 for verification of the effect of the parameter changes.

Parameter	Value	Recommended values [56]
$\rho_{PSS/E}$ (R in figure) – Permanent droop	NO: 0.145, SE&FI: 0.105	0-0.1
r – Temporary droop	1.6	0-2.0, R<r
T_r – Governor time constant	1.3	0.01-30
T_f- Filter time constant	0.05	0.001-0.1
T_g – Servo time constant	0.6	0.01-1
VELM	0.1 / 0.2	0-0.3
G_{MAX}	1.0	0-1.0
G_{MIN}	0.0	0-1.0
T_w – Water time constant	2	0.5-3.0
A_t –Turbine gain	1.01-1.1	0.8-1.5
D_{turb} – Turbine damping	0	0-0.5
q_{NL} – No power flow	0.1	0-0.15

Table 9: Data used for the HYGOV model in the tuned model used in simulations.

From the block diagram above the following is obtained for a stationary situation when assuming the turbine damping is equal to zero.

$$P_{MECH} = A_t h(q - q_{NL}) \qquad \textbf{6-1}$$

$$c = \frac{\Delta\omega}{R}, \qquad q = c * \sqrt{h}, \qquad 0 = 1 - h \qquad \textbf{6-2}$$

$$P_{MECH} = A_t(\frac{\Delta\omega}{\rho_{PSS/E}} - q_{NL}) \qquad \textbf{6-3}$$

The following relationship is obtained for PSS/E to calculate the frequency bias

$$\frac{\Delta P_{MECH}}{\Delta\omega} = \frac{A_t}{\rho_{PSS/E}} \rightarrow \frac{\frac{\Delta P_{MECH}}{M_{BASE}}}{\frac{\Delta f}{50}} = \frac{A_t}{\rho_{PSS/E}} \rightarrow \frac{\Delta P}{\Delta f} = \frac{A_t M_{BASE}}{\rho_{PSS/E} * 50} \qquad \textbf{6-4}$$

In [57] the above equation is also verified. In addition, the droop input in PSS/E must be calculated according to the below formula; hence the value entered in PSS®E is not the effective droop. The desired droop will therefore be called $\rho_{Effective}$.

$$\rho_{PSS/E} = \text{"desired droop"} * A_t * \frac{M_{BASE}}{P_{MAX}} = \rho_{Effective} * A_t * \frac{M_{BASE}}{P_{MAX}} \qquad \textbf{6-5}$$

Normally the frequency bias can be calculated according to this formula

$$R[{}^{MW}/_{HZ}] = \frac{P_{max}}{\rho * 50} \qquad \textbf{6-6}$$

but in this case the $\rho_{Effectvive}$ must be used as seen below

$$R[{}^{MW}/_{HZ}] = \frac{P_{max}}{\rho_{Effective} * 50} \quad \textbf{6-7}$$

and for a sum of n generators the total frequency bias is

$$R_{TOT} = \sum_{i=1}^{n} \frac{P_{MAX,i}}{\rho_{Effective,i} * 50} \quad \textbf{6-8}$$

An overview of the dynamic models at the different buses and the turbine constants (A_t) for the models including a HYGOV is found in "Appendix C - Dynamic models in Nordic44".

6.2.1.1 Effect of changing parameters

The simple test system in "Appendix F - Simple two bus system to test the HYGOV model" is used to verify the effect of changing the most important parameters in the hydro governor. This is shown in the figures below.

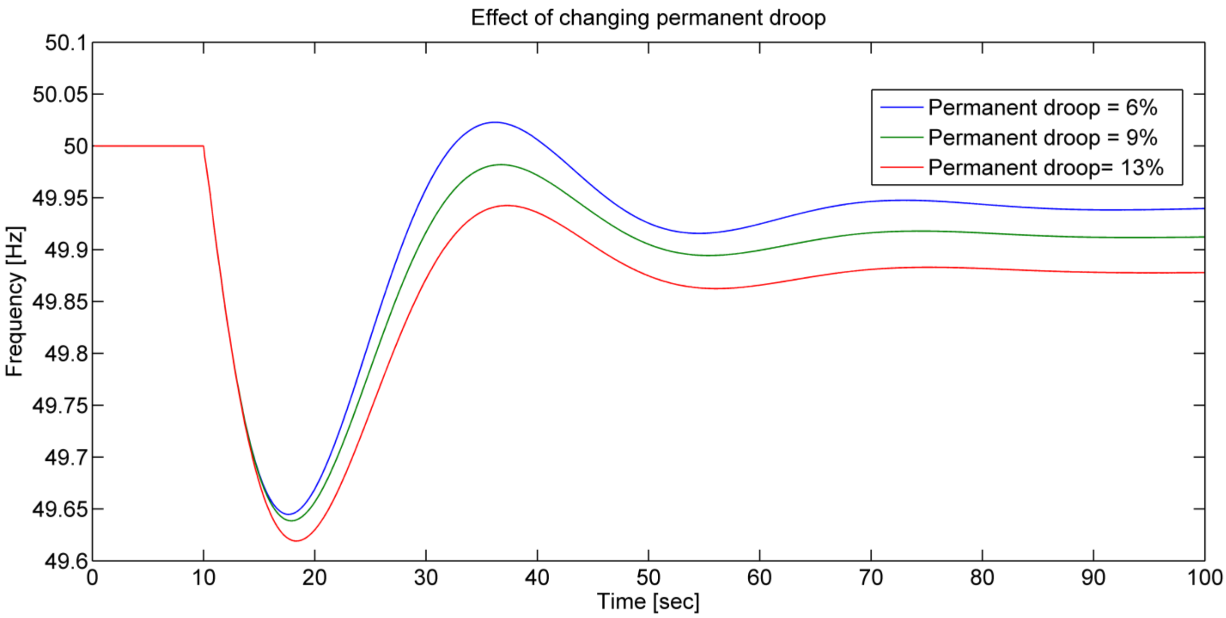

Figure 26: HYGOV - Effect of changing the permanent droop.

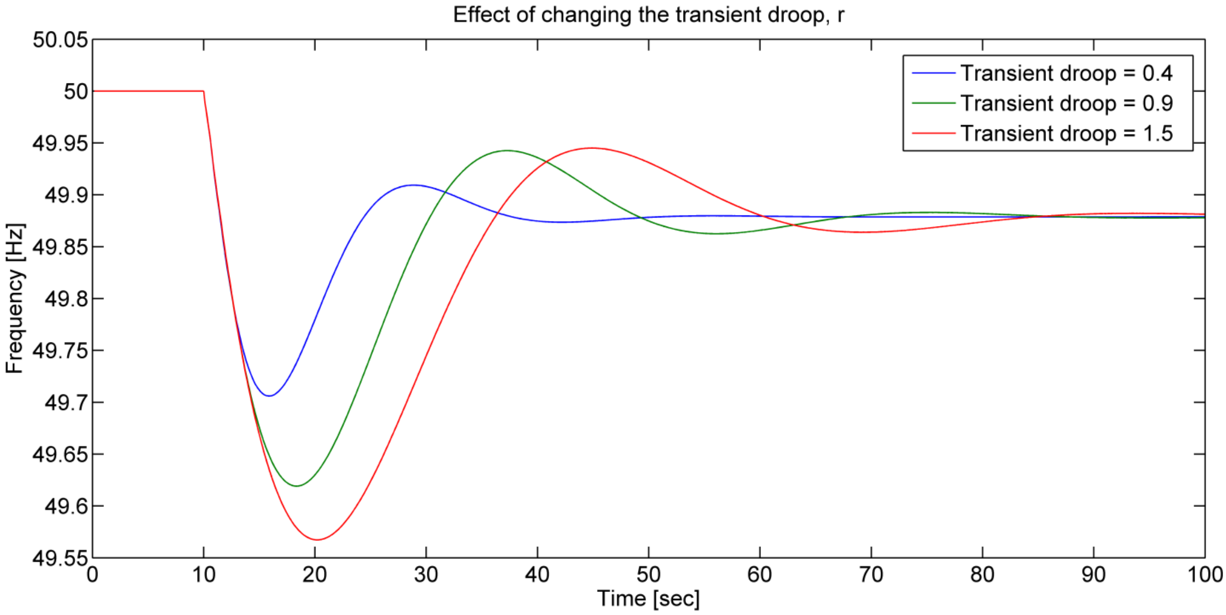

Figure 27: HYGOV - Effect of changing transient droop.

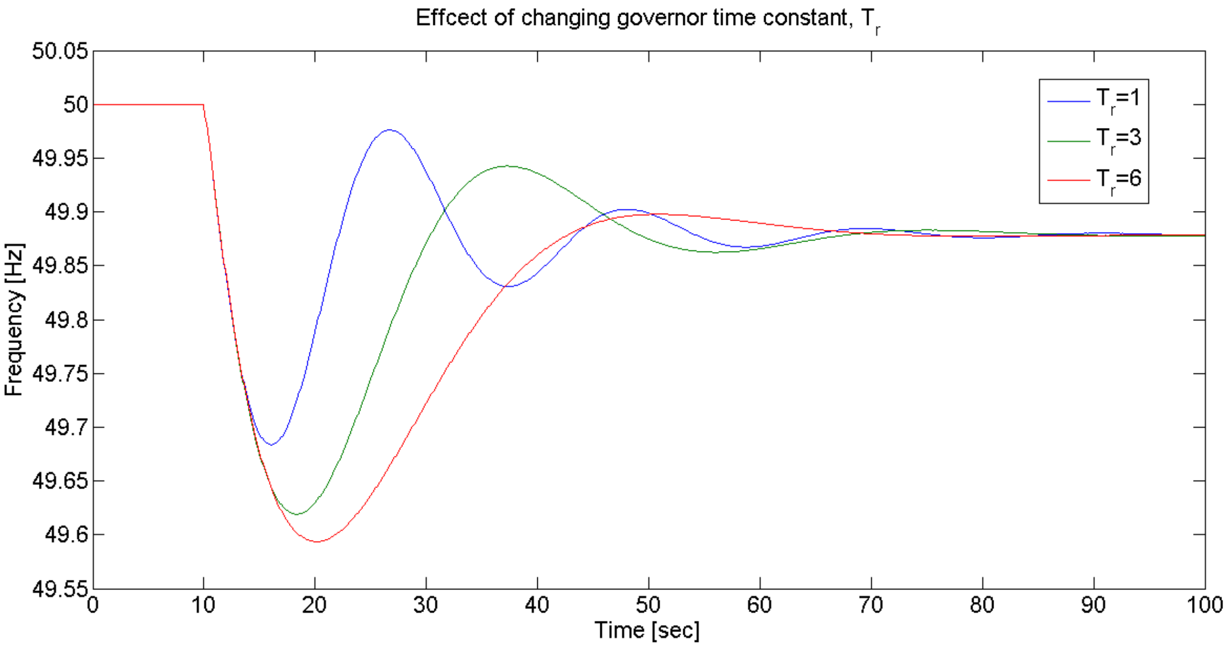

Figure 28: HYGOV - Effect of changing the governor time constant.

6.2.2 *POWER SYSTEM STABILIZER (PSS)*

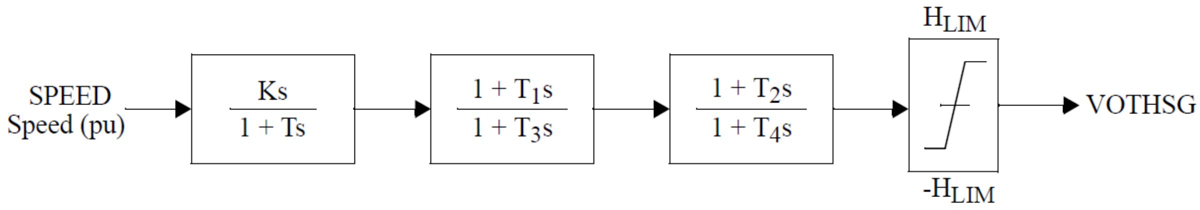

Figure 29: STAB1 model [56].

The power system stabilizer (PSS) STAB1 model (block diagram seen in Figure 29) was chosen instead of STAB2A. This is a simple stabilizer based on speed as an input parameter. Not all units were installed with a PSS, but all existing were replaced and no extra were added.

Parameter	Value	Parameter	Value
K/T	10	**T_2/T_4**	1
T	3	**T_4**	1
T_1/T_3	2.5	**H_{LIM}**	0.1
T_3	0.2		

Table 10: Data used for the STAB1 model [58].

6.2.3 *REST OF THE MODEL*

The thermal governors (IEESGO) are left as they were initially. This governor is inactive (K_1=0), so it will not contribute to the primary response. All exciters used (SEXS, SCRX, IEET2) are left as they were modeled. The GENSAL and GENROU models are also left unchanged.

The model is not up to date regarding 300 and 420 kV lines in Norway.

All the Swedish hydro power is modeled in SE1 and SE2 and all generators in SE3 and SE4 are nuclear or other thermal generators. As this is the dominating production pattern it is modeled like this, but it introduces another challenge: as this is an aggregated model the desired hydropower production might not match the production located in SE1 + SE2. Since this thesis will focus on FCR and inertia, the amount of hydro power is more important than the location of the generation. The amount produced in the different Swedish areas might therefore not reflect the right production.

The dynamic file used in scenario 1, meaning without wind, is found in “Appendix D - Dynamic file”.

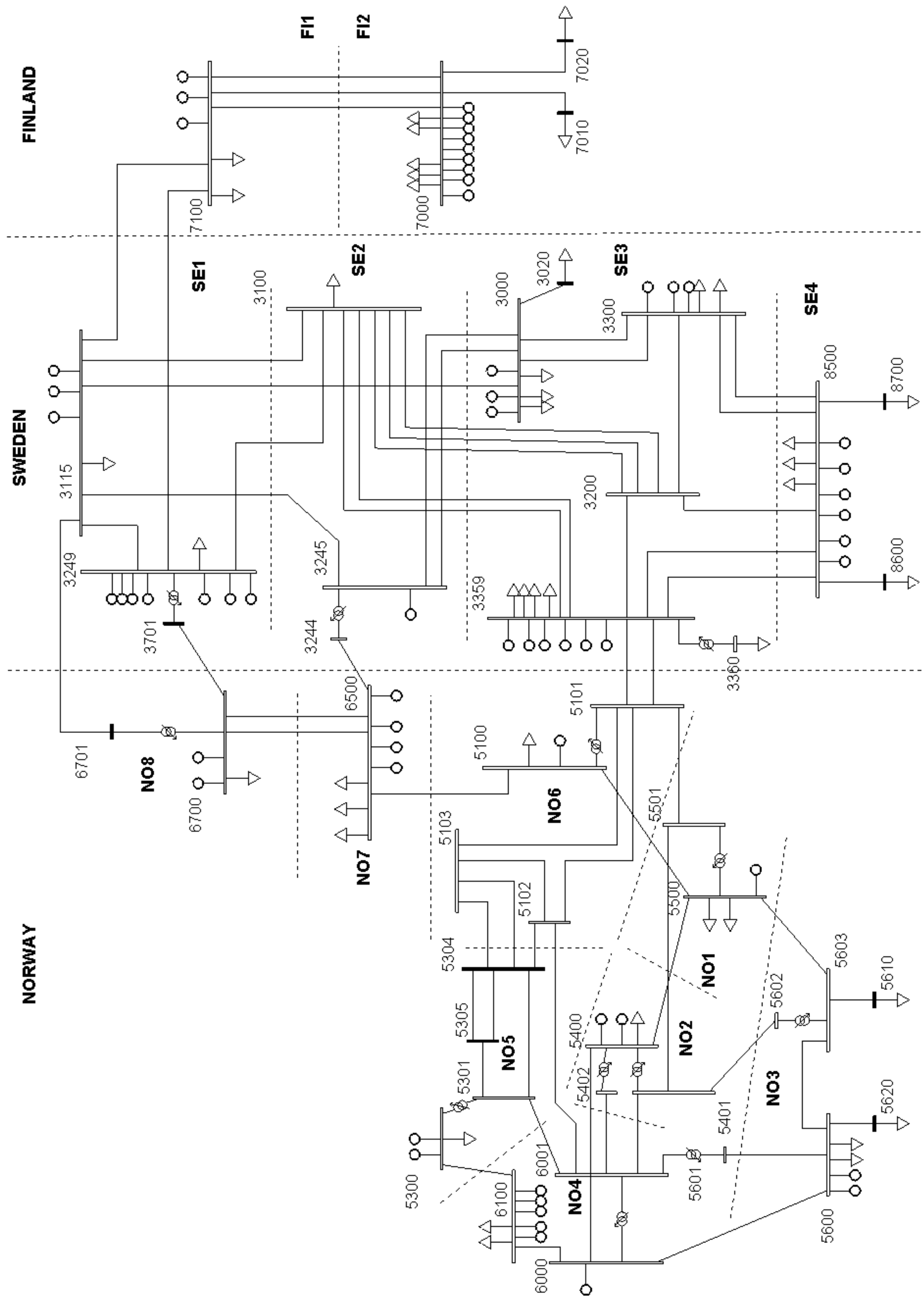

Figure 30: The Nordic44 Model.

6.3 SYNCHRONOUS CONDENSERS

There are no synchronous condensers (SCs) in the model initially. For the compensation scenarios the SC is modeled as a synchronous generator with 0 MW output. A basis for the data is taken from the newly installed synchronous condenser in Feda given from Statnett [27] and listed below.

6.3.1 *GIVEN LOAD FLOW AND GENERATOR DATA*

Rated power	MVA	170
Rated voltage	kV	15
Max reactive production	MVAr	170
Min reactive production	MVAr	-90

Table 11: Load flow data used to model the synchronous condenser.

Frequency	Hz	50	
cos fi		1	
Transient (d-axis) time constant Td'	s	1.202	
Transient unsaturated (d-axis) time constant Td0'	s	10.07	
Subtransient (d-axis) time constant Td''	s	0.029	
Subtransient unsaturated (d-axis) time constant Td0''	s	0.043	
Subtransient unsaturated (q-axis) time constant Tq0''	s	0.15	
Synchronous reactance (d-xis) Xd	ohm	1.945	K: (1.47 p.u.)
Transient reaktans (d-akse) Xd'	ohm	0.224	K: (0.169 p.u.)
Subtransient reactance Xd''	ohm	0.134	K: (0.101 p.u.)
Stationary (q-axis) reactance Xq	ohm	1.853	K: (1.4 p.u.)
Subtransient (q-axis) reactance Xq''	ohm	0.147	K: (0.111 p.u.)
Moment of inertia	kgm2	6900	(H=2)
Pair of poles		1	

Table 12: Generator data used to model the synchronous condenser.

6.3.2 *MODELING IN PSS®E*

For modeling in PSS/E the GENSAL model is used with the above generator data. This model assumes Xq''=Xd'' which is not the case here, therefore 0.101 is used. A simple exciter is used; the SEXS model. Parameters for the SEXS model is seen in table below.

TA/TB	0.1	**TE**	0.1
TB	10	**EMIN**	0
K	100	**EMAX**	4

Table 13: Parameters in SEXS used when modeling the synchronous condenser.

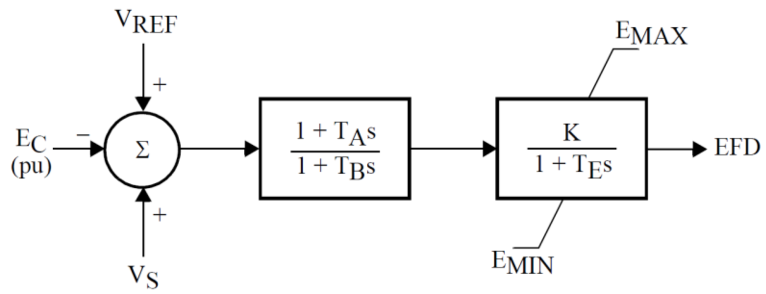

Figure 31: Block diagram of the SEXS exciter [56].

6.4 WIND TURBINES WITH SYNTHETIC INERTIA

Siemens' PSS®E offers four different wind turbine (WT) models. In this thesis the one of interest is WT4, the full scale converter (FSC) unit. However the generic PSS®E WTG models are not intended for frequency excursion studies and they are not designed to reproduce features like synthetic inertia and spinning reserve by spilling wind [56]. As mentioned some manufacturers have included more advanced controls in their variable speed WTs and some of these models are downloadable from the Siemens PSS®E home page. These are more advanced, like the one used here; GE Wind Turbine Generator of the FSC version.

Modeling in PSS®E includes load flow and dynamic modeling; both will be described in the next paragraphs.

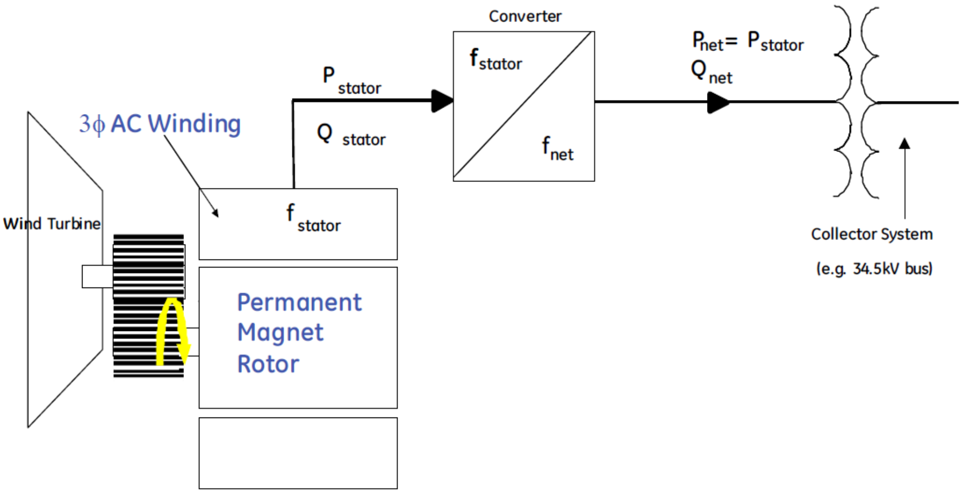

Figure 32: Major components of a GE FSC WTG [59].

6.4.1 *POWER FLOW MODELING*

When studying how wind farms interact with bulk power systems, it is normal to lump several identical wind turbines together into one equivalent wind turbine behind a single equivalent reactance. How many original units lumped into an equivalent machine is represented by a number N. Generator dispatch, M_{BASE} and MVA of the step-up transformer should all be multiplied with N. The implicit step-up transformer representation is not allowed for WTGs. A satisfactory equivalent of collector/feeder system to the point of interconnection is also required. The power flow model is shown in Figure 33.

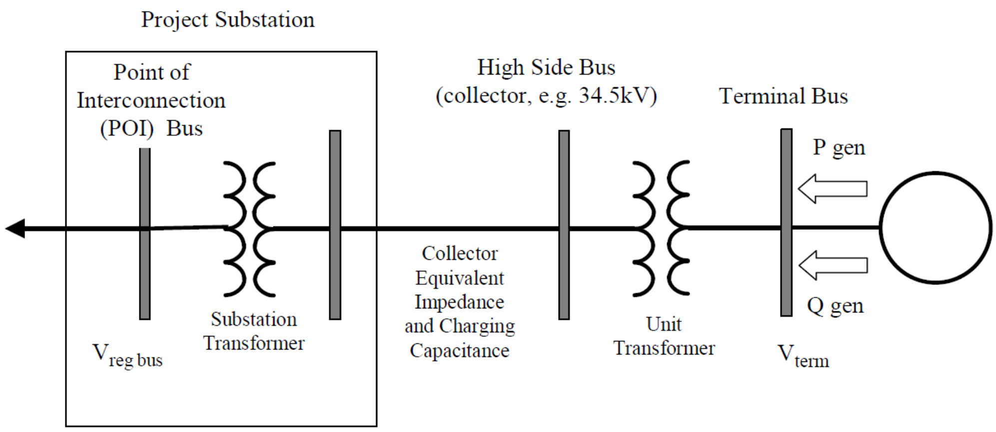

Figure 33: Load flow model of the GE WTG [59].

The aggregated WTG is modeled as a conventional generator and connected to a PV-bus. FSC units are available in three sizes; 2.5, 2.75 and 4.0 MW. In these simulations the biggest one, 4.0 MW is used. The power flow data for this unit are shown in Table 14. The generator terminal nominal voltage will depend on the size of the WTG and the system frequency. For 50 Hz a typical collector voltage at distribution level is 33 kV. The large source reactance is due to the power electronics.

The generator can also measure the voltage on a particular bus, often the point of interconnection (POI), and regulate this voltage by reactive power commands to all WTGs [59, 60].

	GE 4.0 MW
Generator rating, MVA	4.8
Pmax, MW	4.0
Pmin, MW	0.0
Qmax, MVAr	1.93 (for +/- 0.9 pf machines)
Qmin, MVAr	-1.93 (for +/- 0.9 pf machines)
Terminal voltage for 60 Hz, V	690
Terminal voltage for 50 Hz, V	690
XSOURCE, p.u.	99999.
Unit transformer rating, MVA	4.5
Unit transformer impedance, %	6.0
Unit transformer X/R	7.5

Table 14: Power flow data for a wind turbine unit [60].

6.4.2 *DYNAMIC MODELING*

The load flow will provide the basis for the dynamic simulation with its initial condition. An inconsistence between the power flow and the dynamic model will result in an unacceptable initialization.

Overall dynamic model structure consists of three device models; generator/converter model, electrical control model and turbine and turbine control model. The connectivity between them can be seen in Figure 34.

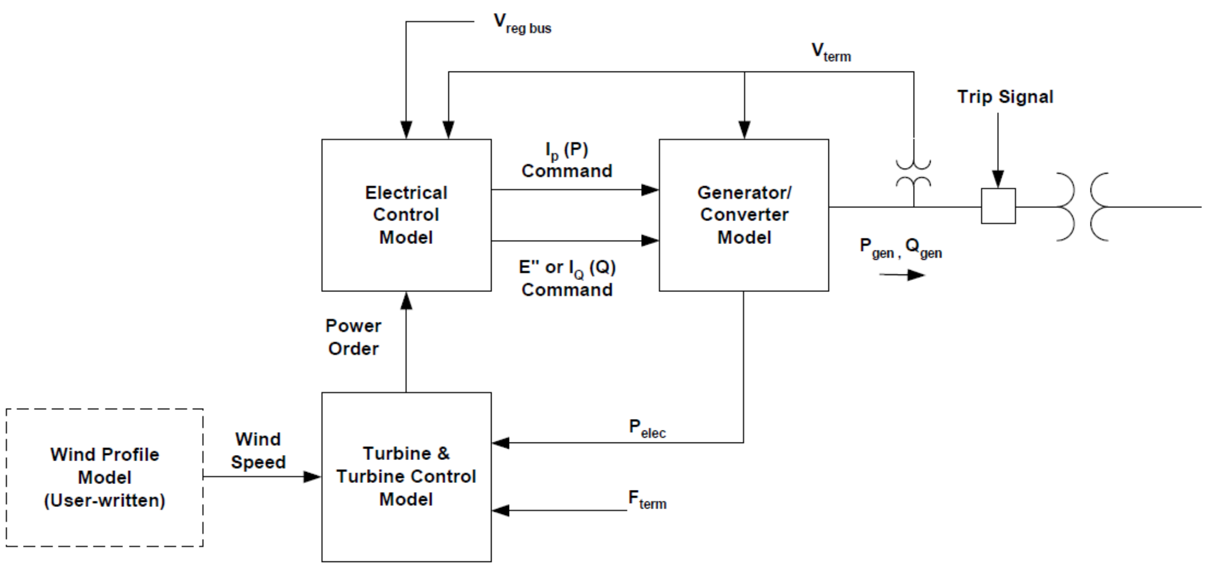

Figure 34: Connectivity between dynamic models [59].

This is similar to the generic models in PSS®E. However, the GE model includes additional models and extended versions of some of the original models. For the FSC 4.0 MW wind turbine the following controllers are included in the dynamic modeling for PSS®E version 33:

- GEWTA2 - GE Wind Turbine Aerodynamics
- GEWTE2 - GE Wind Turbine Electrical Control
- GEWTG2 - GE Wind Turbine Generator/Converter
- GEWTP2 - GE Pitch Control
- GEWTT1 - Two Mass Shaft
- GEWPLT2 - Plotting Output Variables as VARs
- GEWGD1 - Wind Gust and Ramp

Details of the wind models and the parameters are found in "Appendix E - Wind modeling" as default values are used. The part including the WindINERTIA will be further described below.

6.4.2.1 Turbine & turbine control model

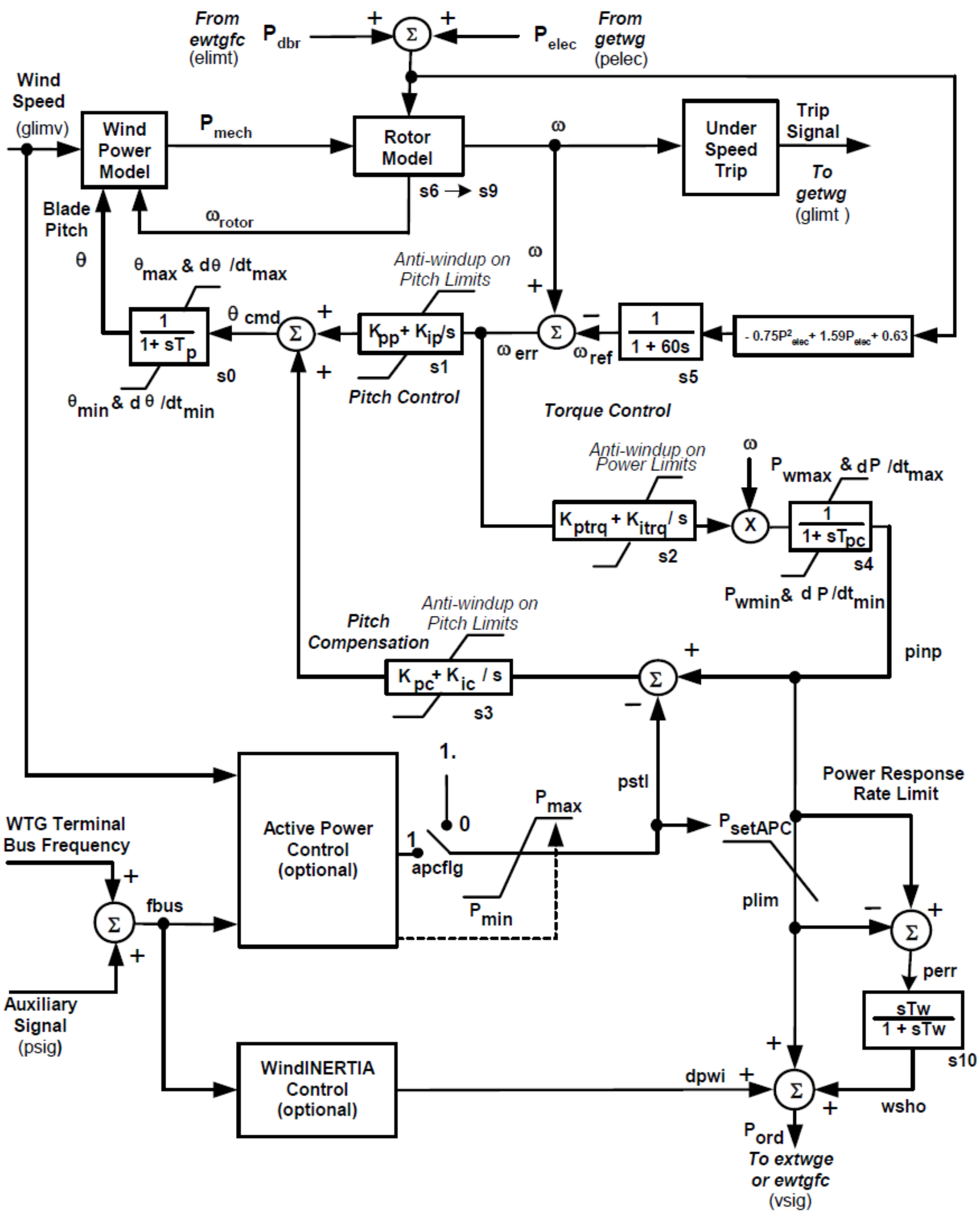

Figure 35: Wind turbine model [59].

The aim of the wind turbine is to get as much power as possible from the available wind keeping operation within the ratings of the equipment. The turbine rotor speed is initially at 120 % as this is default for this type. The turbine control model is seen in Figure 35 and includes pitch control and pitch compensation. Two optional blocks can be activated; Active Power Control (APC) and the WindINERTIA.

The APC could have been used as well showing how WTs can give a primary frequency response, however it is left out as this response is slower and inertial response is of primary interest in this thesis. The WindINERTIA control is asymmetric, but no high frequency events are studied here, hence APC is always deactivated. However, APC is explained in “Appendix E - Wind modeling”.

6.4.2.1.1 *WindINERTIA*

The GEWTE2 (GE wind turbine electrical control) includes the feature WindINERTIA that provides an inertial response capability for large under-frequencies among other advanced controls. This model is therefore more suited for frequency studies. The WindINERTIA control is asymmetric and will only response to low frequencies. High frequencies are taken care of by APC. A temporarily increase in the power output (5-10 % of rated turbine power) lasting for several seconds is the WindINERTIA’s response to a under-frequency event [59]. According to [8] the response can last no longer than 30 seconds. The available wind will limit the power output. In addition physical limitations of WTG components will be restrictive, especially aero-mechanical ratings and speed limits. When a WT is slowed down the aerodynamic lift tends to reduce. This will reduce the mechanical shaft torque and make the speed decline caused by the increased generator electrical torque worse. The blade might be pushed towards an aerodynamic stall and this must be avoided by providing margin above stall. For this reason this control is limited when rotor speed is initially low [59].

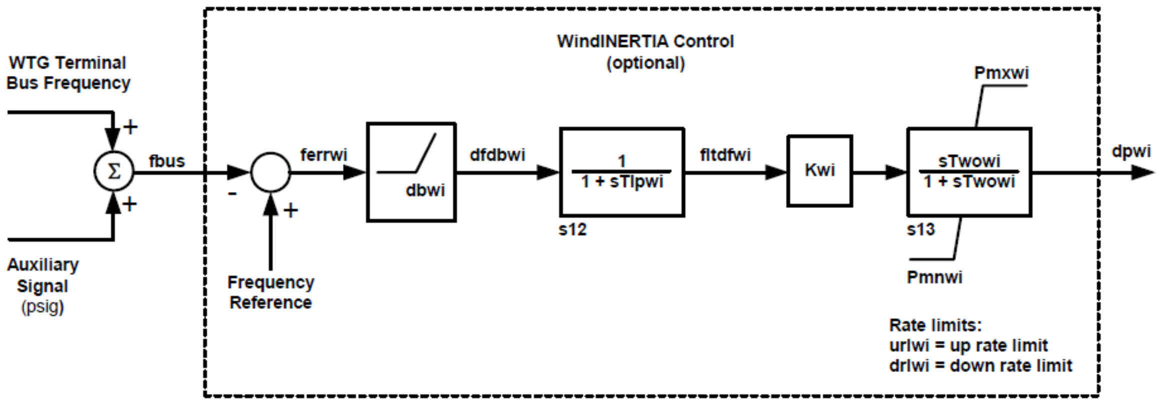

Figure 36: WindINERTIA control [59].

The control is depicted in Figure 36 and the principle is to reveal frequency depressions at the terminals of individual WTGs and increase power output temporarily. If the frequency error is positive, the frequency is low compared to nominal frequency. A dead band will suppress the response until a given threshold is exceeded. In this way WindINERTIA will only react on large events (e.g. outages) and normal, small perturbations in frequency will not pass through the controller. In this thesis a dead band of 0.0025 p.u. will limit the activation. Further, the output from the dead band is filtered, coordinated with the other turbines’ controls and limited. The coordination will modify several gains and time constants in other parts of the control. As shown in the figure; T_{lpwi} is the filter time constant, K_{wi} is the gain value and T_{wowi} is the time constant for the wash-out filter component. The wash-out filter is a high pass filter that will reject steady state inputs and pass through transient inputs [4, 59].

Variable name	Recommended Value
K_{wi}	10
db_{wi}	0.0025
T_{lpwi}	1
T_{wowi}	5.5
url_{wi}	0.1
drl_{wi}	-1.0
P_{mxwi}	0.1
P_{mnwi}	0.0

Table 15: Recommended values for the WindINERTIA model [59].

6.4.3 *VERIFYING OF THE SYNTHETIC INERTIA*

Verification of the synthetic inertia feature was done by comparing two simulations. The first one includes synthetic inertia on the modeled wind and in the second the same amount of inertia is replaced by physical inertia in a thermal generator. The thermal unit has H=5.97 and M_{BASE}=1012.35 MVA. The wind turbine has a M_{BASE}=984 MVA and by setting K_{WI}=6.1420 the relationship H* M_{BASE}=K_{wi}* M_{BASE} is exact, hence the same amount of "inertia" is replaced. This makes the frequency responses for the two cases almost identical as seen in Figure 37, hence the synthetic inertia is comparable to the physical. Plots of electrical output and wind speed can be seen in 7.6 under Scenario 3b and 3c and is therefore not included here.

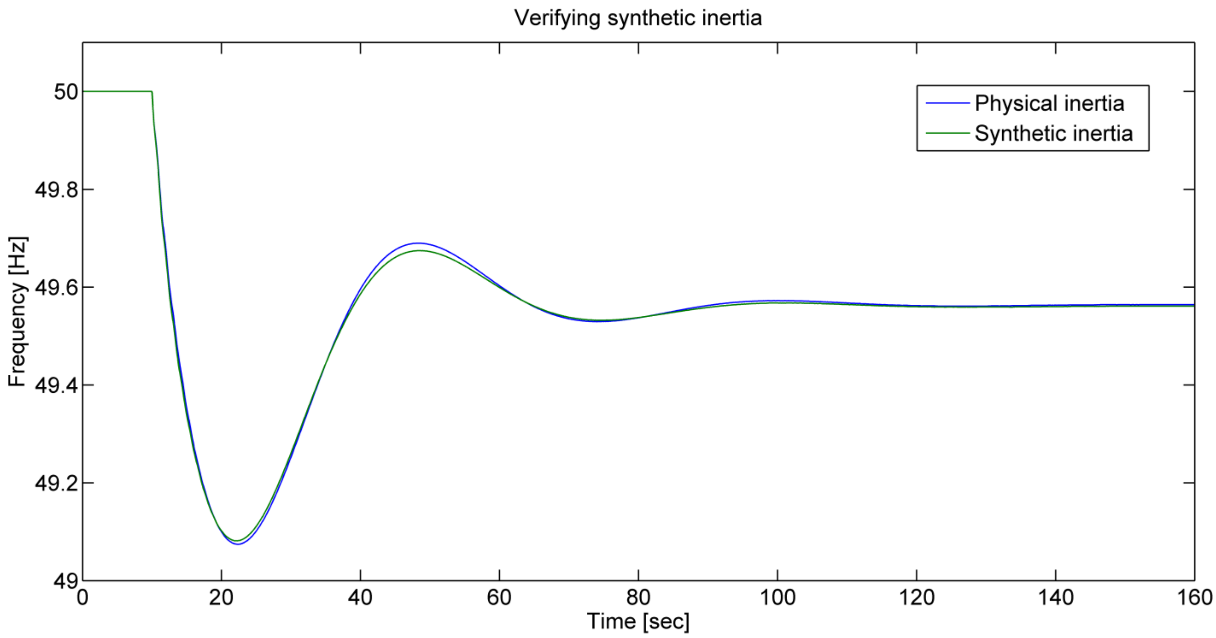

Figure 37: Effect of replacing physical inertia by synthetic inertia.

	Nadir [Hz]	Time to nadir, t_{min} [sec]
Synthetic inertia	49.0818	22.1
Physical inertia	49.0749	22.3

Table 16: Frequency indicators verifying synthetic inertia.

6.5 VSC HVDC

In PSS®E there is a prebuilt model of a VSC HVDC line. For the purpose of frequency response studies, it is not sufficient as there is no possibility to measure the frequency and control the power in this prebuilt model.

For simplicity the GE wind model will also be used to demonstrate the synthetic inertia on VSC HVDC cables. This can be done in this case as all simulations of interest will be import scenarios. It is not very wrong to assume that the same principle is applicable for the control mechanism; having the frequency deviation as an input, including a dead band, washout and gain to get an increased power output.

One modification must be done. As the wind turbine has the availability to slow down and release energy, the cable will be forced to work on a lower import level than maximum capacity or eventually be dimensioned for the possibility to increase power for several seconds. However, to utilize the wind model in the best way it is ran on rated capacity. In this case the rated capacity is only 85 % of the real cable capacity as this is the import level in the scenarios and the maximum output increase is 10 %.

Another important factor will be wrong using this model. The wind turbine needs a recovery phase after the initial increase in energy, while for the VSC HVDC cable this will not be necessary as the source (connected country) can be assumed unlimited.

7 SIMULATIONS AND RESULTS

Three scenarios will be given attention. The first is a reference scenario for tuning, while the two others are low load scenarios in the past and in the future. Power flow solution and dynamic simulations will be conducted in PSS®E. Plotting will be done in MATLAB. Details of the scenarios are given below.

7.1 DIFFERENT SCENARIOS

- Scenario 1: Reference scenario (05.03.2015) when a sudden loss of 1110 MW in SE3 occurred. This is used for tuning of the model. This outage will be used in all scenarios.
- Scenario 2: Low load summer day (23.06.2013).
    - Initial frequency 49.9 Hz.
- Scenario 3: Future 2020 scenario with high import on HVDC links (85 % of total 2020 HVDC-capacity). Load adjusted accordingly and production given by Statnett. Three versions:
    - 3a) Production portfolio as "today" (only small amount of wind, 4 %).
    - 3b) Approximately 20 % wind in the production portfolio.
        - Possibility of compensating with synthetic inertia.
        - Compensating with synchronous condenser.
        - Initial frequency 49.9 Hz.
    - 3c) Similar to 3b, but synthetic inertia opportunity on VSC HVDC cables also included, meaning a total of 30 % synthetic inertia in the system.

7.2 WHY THESE SCENARIOS

The first scenario is only used to tune the model as an event was needed to adapt the frequency response. The second scenario is a real operation scenario from 23.06.2013. The point of time was found to have relatively low load and quite high import in Norway. The purpose of this scenario is to check the level of inertia with production portfolio as "today". This is important as there is a need to know the status of today to better estimate the problems in the future. Scenario 3 is a 2020 future scenario with high import. Different versions will be tested and "worst case" production share from Statnett is used in 3b. High wind production and import will reduce the inertia in the system and this is the area of interest for the thesis. How will the system handle a 1110 outage with low levels of inertia? In this scenario possibilities for compensation are also investigated. In addition in each scenario it is considered whether the FCR requirements are fulfilled or not, and their relation to the inertia level.

7.3 GENERAL ASSUMPTIONS APPLICABLE FOR ALL SCENARIOS

- Frequency is always measured at bus 5101, Hasle.
- The loss of the 1110 MW production unit is represented by bus 3359 unit 1 in SE3.
- The same outage is tested for all scenarios.
- No difference is made when thermal and nuclear production is modeled.
- There is no division of hydro and small scale hydro. H-constants are kept unchanged in the model and all hydro production is distributed arbitrary on these.
- All generators are attempted to have an approximately 85-90 % production of P_{MAX}, however this is not possible to fulfill at all time. Too avoid shrink or enlarge generators too much some wiggle room is accepted. This also includes moving production from one area to another within the same country.

- Left over generators are marked out of service and will therefore not contribute to production, frequency response or inertia.
- Reactive power on generation and load is only adjusted if necessary and not in scale with the active power.
- In the PSS®E model the data from Nord Pool Spot are used. There is a deviation from the production data given by the TSOs, non significant errors and the production data is therefore used as a basis to get the right share between production types.
- If wind power is modeled, one turbine will represent a lumped amount of wind turbines as only one wind farm is modeled in each country.
- All wind turbines are of the same type and size (4 MW full scale converter unit).
- Wind speed is assumed constant during simulation (14 m/s) and the "gust and ramp" model that provide varying wind speed is not active.
- Wind turbines are assumed to run at rated capacity (P_{Max}).

FCR requirements that must be fulfilled were explained in 3.1. The division between FCR-N and FCR-D makes it difficult to study both at the same time. However FCR-N is meant for small operational disturbances (e.g. ramping on HVDC cables or normal imbalances due to load changes) and only +/- 0.1 Hz from 50 Hz. In this thesis an actual distribution is studied and focus will be on FCR-D. For simplicity worst case scenarios are therefore run at initial frequency 49.9 Hz and FCR-D requirements are considered.

7.4 Scenario 1 - Tuning

7.4.1 *Production data*

This is a reference scenario from 05.03.2015. Data is given in the tables below. Note that DK2 is omitted since it is not modeled in the Nordic44 model.

05.03.2015 11:00	NO	SE	FI	Total
Consumption [MW]	18 639	19 768	10 831	49 238
Production [MW]	23 089	20 723	8 659	52 471

Table 17: Scenario 1 - Data for production and load from Nord Pool Spot [61].

05.03.2015 11:00-12:00	Nuclear [MW]	Hydro [MW]	Small Hydro [MW]	Thermal [MW]	Wind [MW]	Solar [MW]	Total [MW]
Norwegian	0	22 542.07 (96.2%)	235.93 (1.0%)	376 (1.6%)	268 (1.1%)	0	23422
Swedish	6677.31 (33.5%)	11924.4 (59.8%)	-	1192.9 (6.0%)	143.85 (0.7%)	12.88 (0.064%)	19951.3
Finish	2743.00 (31.5%)	2154 .00 (24.7%)	-	3808 .00 (43.7%)	8 .00 (0.09%)	0	8713
Total	9420.31 (18.1 %)	36 620.47 (70.3%)	235.93 (0.5%)	5376.9 (10.3%)	419.85 (0.8%)	12.88 (0.02%)	52 086.3

Table 18: Scenario 1 - Division between type of production. Given from Statnett, Fingrid and Svenska Kraftnät [62].

During this hour there was a planned outage of 1110 MW (Ringhals Block 4) in SE3. Figures and data showing the frequency response were given from Statnett. The data plotted can be seen in Figure 38. The model will be tuned according to this response. In addition data for the flow from NO1-SE3 was given to adjust the permanent droop in Norway relative to Sweden and Finland.

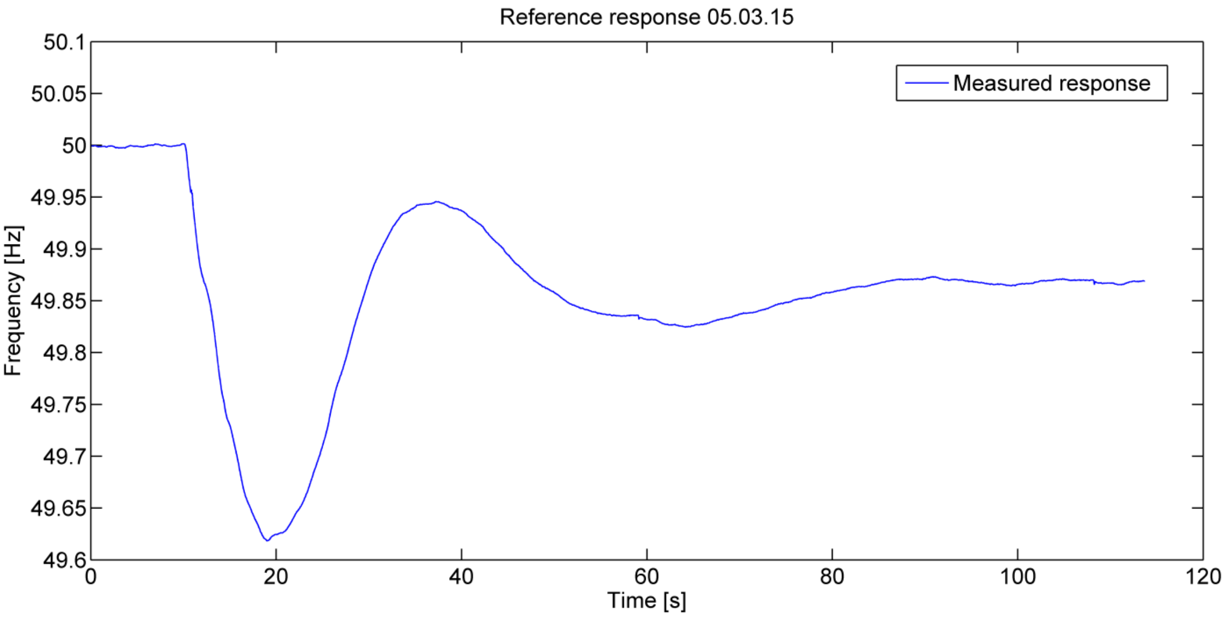

Figure 38: Plot of the original response. (offset to 50 Hz).

A graphical way of determining the inertia was attempted from the response. This is done by looking at the first seconds of the frequency drop and drawing a tangent line to get the slope (df/dt). Since the response is not a straight line it is difficult to decide the slope of it. However, two alternatives show an idea of the initial frequency drop (see black lines in Figure 39).

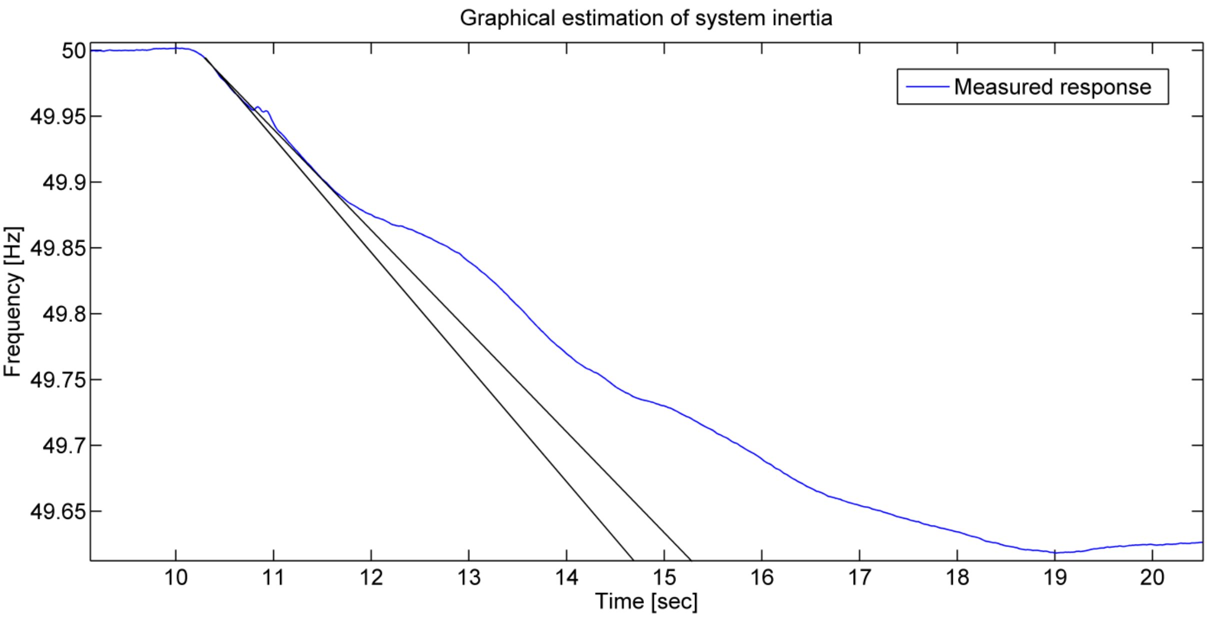

Figure 39: Tangents to estimate the inertia.

Equation 2-8 was used to estimate the system inertia out of the two lines, meaning the inertia should be around these levels (as shown in the equations below).

$$\frac{df}{dt} = f_n \frac{P_m - P_e}{2H} \rightarrow H_{sys} = f_n \frac{\Delta P}{2 * \frac{df}{dt}} = 50 \frac{1110}{2 * \frac{0.3878}{4.33}} = 309.8\ GWs$$

$$\frac{df}{dt} = f_n \frac{P_m - P_e}{2H} \rightarrow H_{sys} = f_n \frac{\Delta P}{2 * \frac{df}{dt}} = 50 \frac{1110}{2 * \frac{0.3878}{4.96}} = 354.9\ GWs$$

From Equation 2-12 the frequency bias can be obtained. The frequency deviation of 0.1330 Hz is between the initial frequency and the steady state frequency (shown as Δf_{ss} in Figure 9). As the steady state frequency oscillates a bit, an average of the value between 90 and 113 seconds was used and calculated as 49.8685 Hz. Hence the difference between the initial frequency before the loss at 50.0015 Hz and 49.8685 Hz is 0.1330 Hz.

$$R_{Nordic\ System} = \frac{\Delta P}{\Delta f} = \frac{1110}{0.1330} = 8345.9\ \frac{MW}{Hz}$$

To find the share of the frequency bias between Norway and Sweden the flow between NO1 and SE3 (Hasle) was monitored prior to and after the event. Δ(NO1-SE3) was found to be 474 MW and therefore the contribution from southern Norway is

$$R_{Southern\ Norway} = \frac{474}{1110} * 8345.9 = 3563.9\ \frac{MW}{Hz}$$

7.4.2 *PSS®E MODELING*

Assumptions/modifications for Scenario 1:

- Wind production is negligible for all countries in this scenario and therefore no wind production is added to the original model.
- Ahead of the actual event the frequency was adjusted artificially high, however this is offset to 50 Hz and tuned from here.
- All hydro power in Sweden is modeled in SE2/SE1 and this scenario requires more hydro production than the amount located here. This is solved by moving some production from SE3 to SE1/SE2 to get the right amount of hydro.
- To avoid running on low power factor and shrinking a generator too much; 244 MW of the generation in SE3 were moved to SE4.

	Total	**Norway**	**Sweden**	**Finland**
Hydro power installed [MW]	43 602.30	26 945.56	13 637.78	2700.00
Hydro power online [MW]	42 283.33	25 945.56	13 637.78	2700.00
Running hydro [MW]	37 053.00	23 088.00	11 819.00	2146.00
Spinning hydro reserves [MW]	5549.27	2857.60	1818.78	554.00

Table 19: Scenario 1 - Hydro power details.

Hydro power details are seen in Table 19. This scenario includes large amounts of spinning reserves. Production and load data are given in "Appendix A - Production/load data".

7.4.3 *LOAD FLOW*

The load flow converges, but does not reflect the real situation and unfortunately the model has several weaknesses. The model might be too simplified to get a realistic picture. Some of the areas (e.g. NO5 and NO2 as well SE1 and SE2) are not properly modeled and assumptions explained in chapter 6.2 were taken to distribute the production and load in the best way. The initial Norwegian capacity in the model is approximately 21 000 MW, but in this reference scenario the production in Norway was above 23 000 MW, hence the capacity (P_{Max} and M_{Base}) had to be increased.

Production in southern Norway was especially high, and this was where most of the generator capacities were increased. This created overloaded branches and transformers in southern Norway. The same happened in northern parts of Sweden. This was solved by reducing impedances and will be explained in 7.4.4. Probably increased production capacity and uncertainty of where to place the production/load worsened the load flow and, in a dynamic perspective, contributed insufficient damping.

A graphical view of the actual scenario load flow and the simulated load flow can be seen in "Appendix B - Load flow data", and several deviations between the two versions are seen.

7.4.4 *DYNAMIC SIMULATION*

Initially the damping in the model was unsatisfactory. The PSSs was changed and the damping in the model was improved by replacing the PSS model STAB2A with STAB1. As mentioned above several branches were overloaded when running the load flow. This also affected the dynamic simulations. The problem was solved by reducing the impedances. All impedances were multiplied by a factor of 0.6 throughout the model. This reduced the overloading of the branches and improved the damping in the system, as reduced impedances in practice correspond to increased ratings. The ratings on the lines were not checked against realistic values on beforehand; however, solving it this way it is no longer a limiting factor.

The inertia constants have been left as they were in the model initially. The HYGOV parameters are described in an own chapter. As this is not a low production scenario, most M_{Base} and P_{Max} values were used as they were initially, unless when the generator had to increase in size. As already explained, this was the case in some areas (NO2, NO4, NO5, SE1 and SE2) as the initial capacity could not fulfill the production given in Scenario 1. In these cases, the ratio between P_{Max} and M_{Base} were kept when changes were made.

The next problem was to get the correct frequency response. The response started too early and adjusting the HYGOV parameters was not sufficient to get the right response. Another solution was found; it seemed like the loads were too dependent of the voltage. The loads are given as a reactive and an active part. In dynamic simulations this is converted according to the ZIP-model into percentages of current, admittance and power (I/Y/P). Initially the active load was converted to 60 % constant current and 40 % constant admittance, and the reactive load to 100 % constant admittance. The active part was changed to 15 % constant current, 15 % constant admittance and 70 % constant power. By doing this the response improved a lot compared to the measured one. By further reducing the voltage dependence by setting the mentioned settings to 10-10-80 (I-Y-P), the response got faster. The different responses, including the measured one, is depicted in Figure 40.

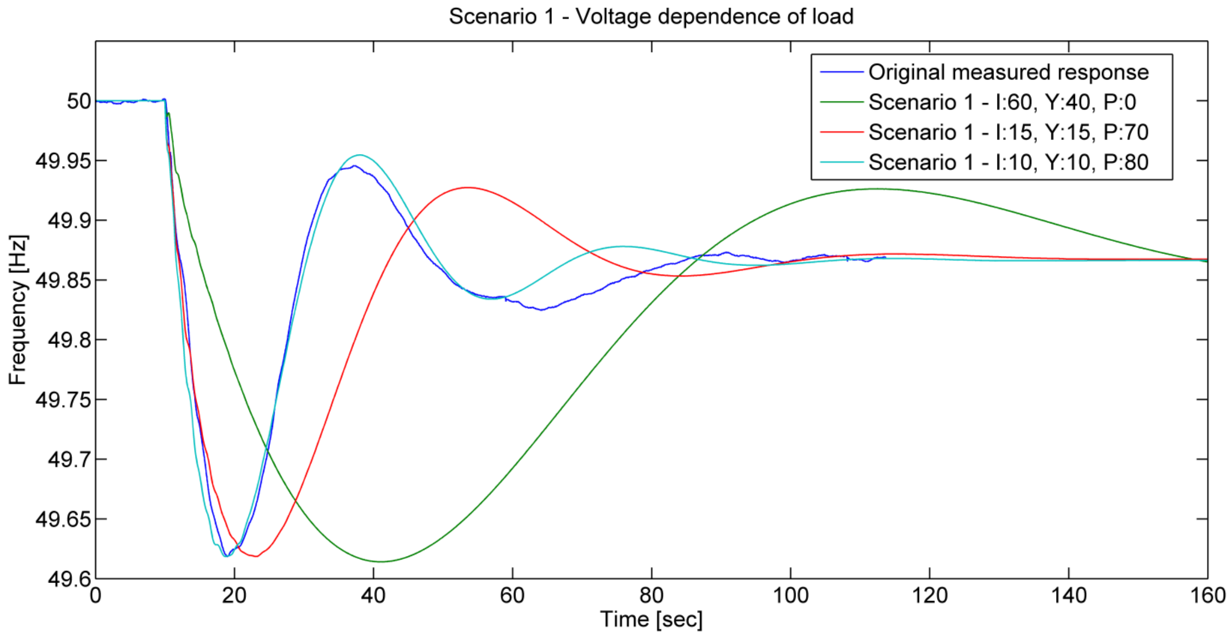

Figure 40: Scenario 1 - Voltage dependence of the load.

The HYGOV parameters were used to tune the response and are not the same for the three versions in Figure 40, as different values were required to achieve the right nadir (see Table 20). The 10/10/80 division and a low T_r made it possible to follow the initial drop and the overshoot quite well, but the response oscillates too fast after this.

Load (I/Y/P)	**10/10/80**	**15/15/70**	**60/40/0**
$\rho_{PSS/E}$ - Permanent droop	NO: 0.145, SE&FI:0.105	NO: 0.145, SE&FI:0.105	0.14
r – Temporary droop	1.6	2	6
T_r – Governor time constant	1.3	2	2
T_f- Filter time constant	0.05	0.05	0.05
T_g – Servo time constant	0.6	0.6	0.8
VELM	0.1 / 0.2	0.1 / 0.2	0.1 / 0.2
G_{MAX}	1.0	1.0	1.0
G_{MIN}	0.0	0.0	0.0
T_w – Water time constant	2	1.55	2.5
A_t –Turbine gain	1.01-1.1	1.01-1.1	1.01-1.1
D_{turb} – Turbine damping	0	0	0
q_{NL} – No power flow	0.1	0.1	0.0

Table 20: HYGOV parameters used in Figure 40.

Even though it is far away from the initial load conversion, the load division used further in the thesis is 10-10-80 as this gives the result closest to the real response. There are still some small differences, but the response is good enough, as the first seconds of the response is the major field of interest for this study. The measured response and the simulated response can be seen in Figure 41.

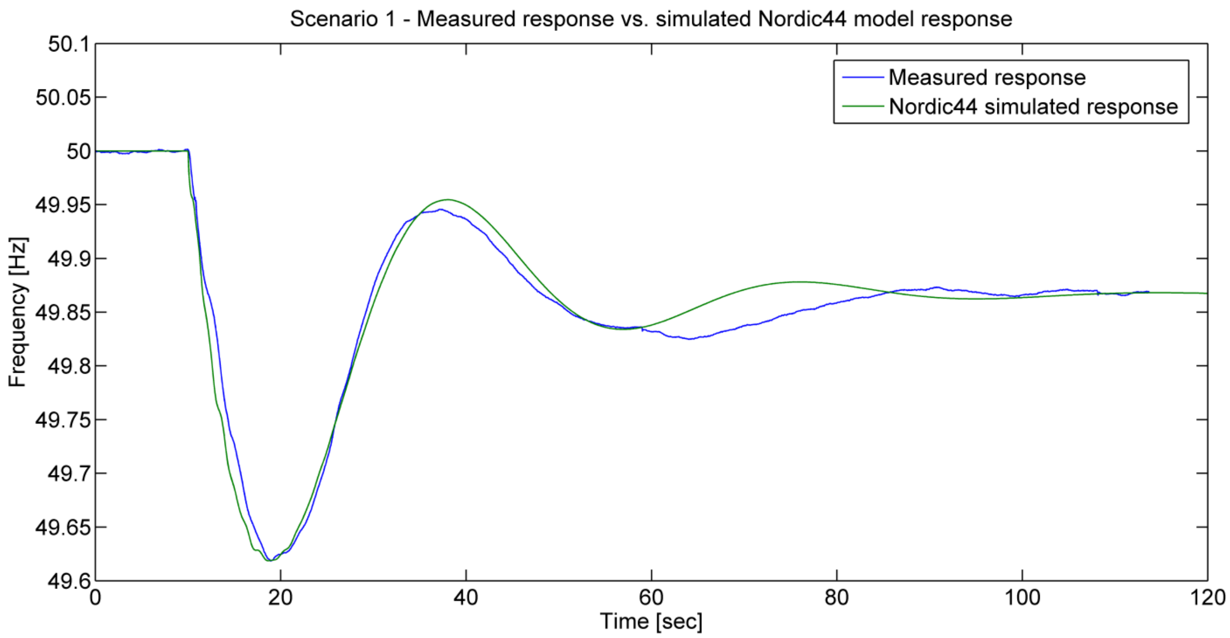

Figure 41: Scenario 1 - Measured frequency response and Nordic44 frequency response

	Nadir [Hz]	Time to nadir, t_{min} [sec]	Δf_{ss} [Hz]	f_{ss} [Hz]
Measured response	49.6183	18.92	0.1330	49.8670
Nordic 44 response	49.6186	18.70	0.1336	49.8664

Table 21: Scenario 1 - Frequency indicators.

Inertia in the system is found by summing the products of the individual inertia constants and their machine base as seen below. For this scenario the total model inertia is calculated to be slightly lower than the graphical estimate.

$$\sum_{i=1}^{n} H_i M_{BASE,i} = 282.52\ GWs$$

During simulations, by adjusting the permanent droop in SE/FI and NO, a Δ(NO1-SE3) of 483 MW is obtained. This is quite close to the measured Δ(NO1-SE3) of 474 MW. The permanent droop ended at 14.5 % in Norway and 10.5 % in Sweden and Finland. These values are high, also when taking into account that the $\rho_{Effective}$ or the effective droop (see 6.2.1) is somewhat lower than the droop used in PSS®E.

The calculated frequency bias for this scenario is

$$\sum_{i=1}^{n} \frac{P_{MAX,i}}{\rho_{Effective,i} * 50} = 8043\ MW/HZ$$

This scenario is run at 50 Hz and the frequency bias is above the requirement for FRC-N and FCR-D.

Figure 42 shows the total response from all hydro units in the system. Total increase in hydro production is 1176 MW and 5 seconds after the fault the increased output is 569 MW, which is above 50 %. The requirement of 100 % activation after 30 seconds is also fulfilled, but not at steady state value.

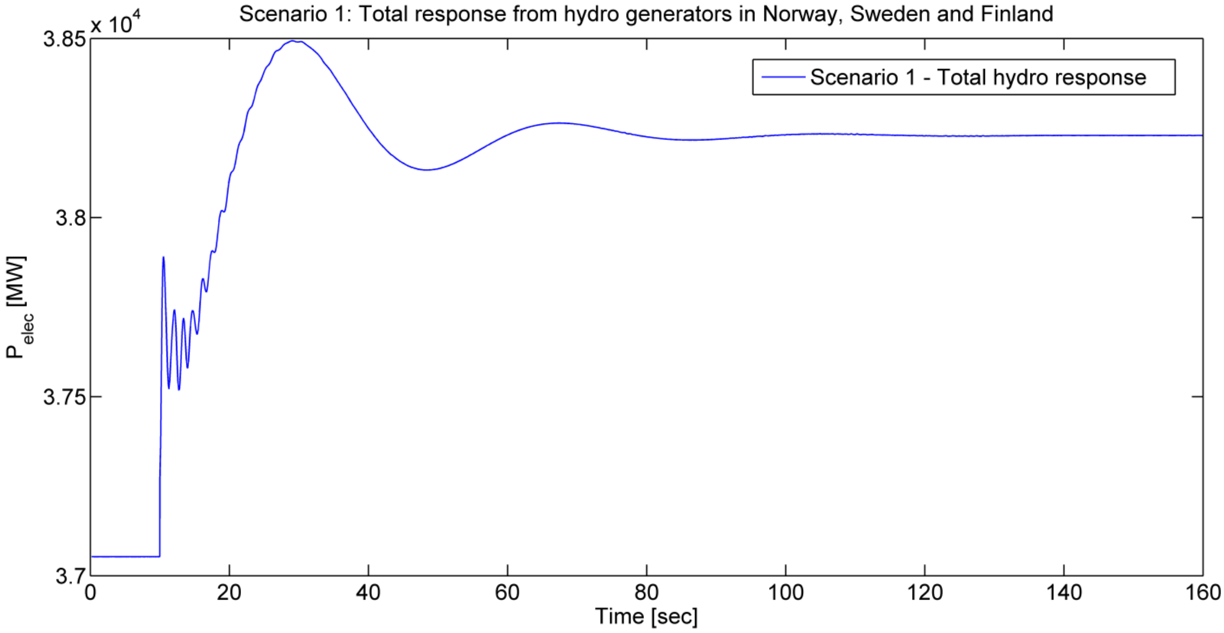

Figure 42: Scenario 1 - Simulated P_{elec} for hydro generators in Norway, Sweden and Finland.

Load and the nuclear/other thermal generators do also respond to the frequency event. In Figure 43 the common response for all nuclear/other thermal units are shown, note that the 1110 MW unit lost is included and causes the initial drop that makes it difficult to see the inertial response. Regardless of this, the point is that the difference between the pre outage production and the steady state production differ from the size of the lost unit by approximately 40 MW. This means these units also respond to frequency deviations in a small manner as their total output is increased slightly, even though their governors are inactive.

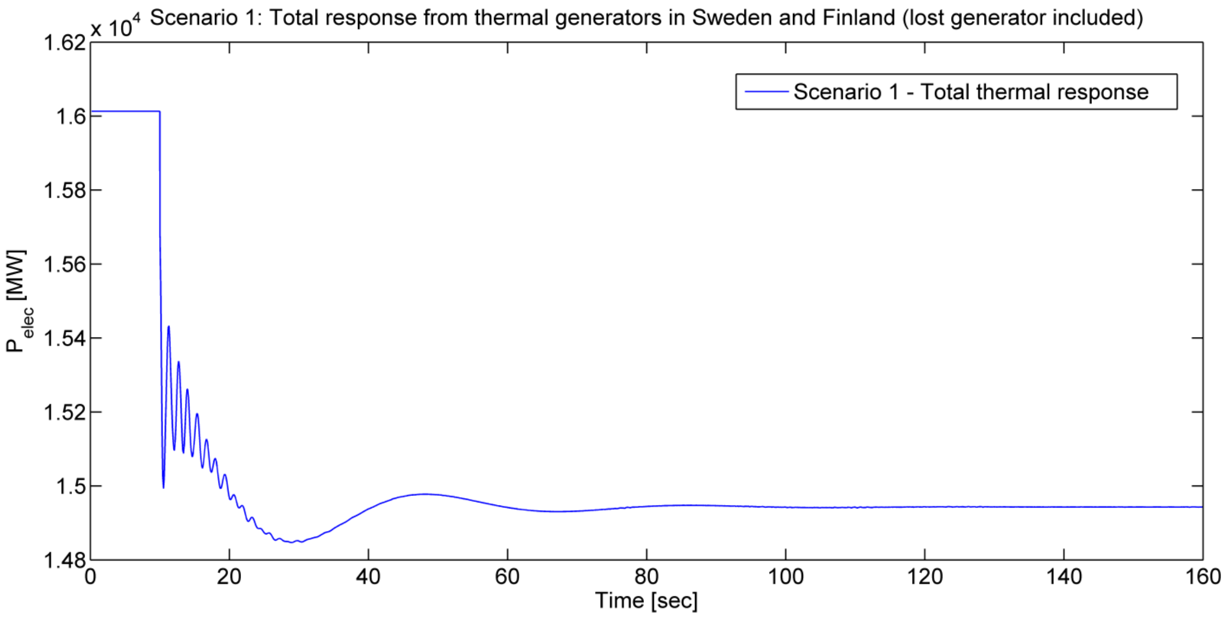

Figure 43: Scenario 1 - Simulated P_{elec} for thermal/nuclear generators in Sweden and Finland (lost unit included).

The load response is shown in Figure 44. There is a deviation between pre-disturbance and steady state value here as well (by 47 MW). As expected the hydro governors contribute most to the frequency response, but load and thermal/nuclear generator units are not unaffected by the frequency as verified by these figures.

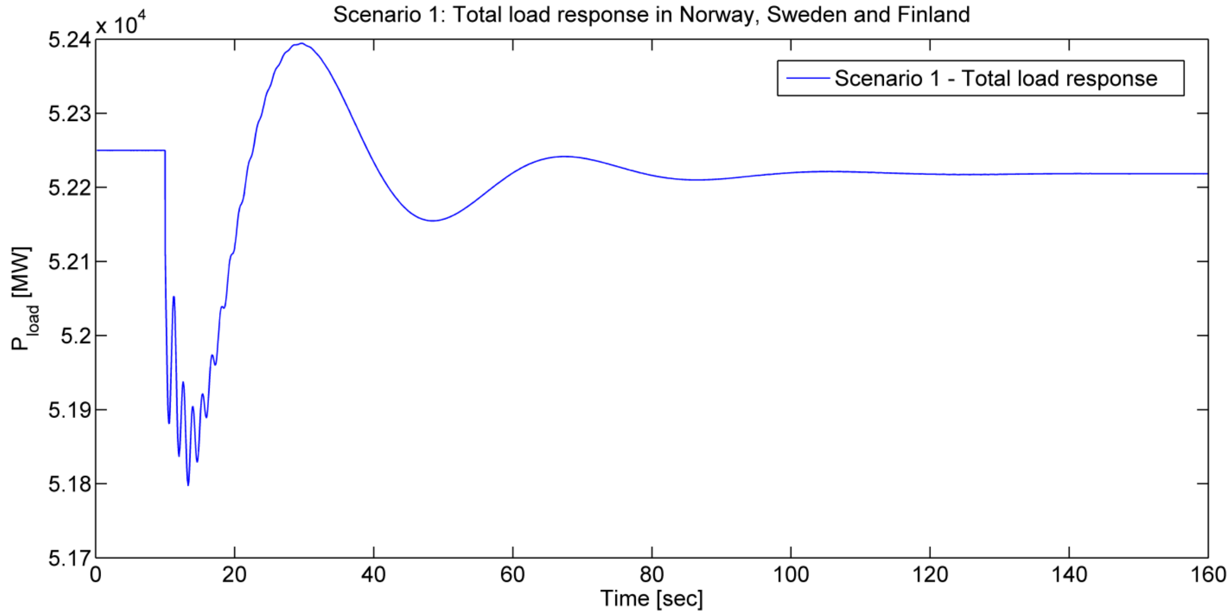

Figure 44: Scenario 1 - Simulated P_{load} for loads in Norway, Sweden and Finland.

7.5 SCENARIO 2

7.5.1 *PRODUCTION DATA*

This is an actual summer day in June 2013 with low load, low production and relatively high import. Data is given in the tables below.

23.06.13 05:00	**NO**	**SE**	**FI**	**Total**
Consumption [MW]	9160	9185	5125	23 470
Production [MW]	6403	11481	4684	22 568

Table 22: Scenario 2 - Production and load data from Nord Pool Spot [61].

23.06.2013 05:00-06:00	**Nuclear [MW]**	**Hydro [MW]**	**Small Hydro [MW]**	**Pump Hydro [MW]**	**Thermal [MW]**	**Wind [MW]**	**Total [MW]**
Norway	0	5708.36 (87.9%)	289.35 (4.4%)	-42.80 (-0.6%)	400.95 (6.2%)	138.15 (2.1%)	6494.45
Sweden	7420.77 (68.3%)	2414.11 (22.2%)	-	-	257.82 (2.4%)	772.35 (7.1%)	10 865.00
Finland	2706.00 (57.8%)	739.00 (15.8%)	-	-	1205.00 (25.8%)	29.00 (0.6%)	4679.00
Total	10 126.77 (45.9%)	8861.47 (40.2%)	289.35 (1.3%)	-42.8 (0.19%)	1863.77 (8.4%)	939.5 (4.3%)	22 038.45

Table 23: Scenario 2 - Division between type of production. Given from Statnett, Fingrid and Svenska Kraftnät [62].

7.5.2 *PSS®E MODELING*

Assumptions/modifications for Scenario 2:

- There is no wind power modeled in Norway and Finland as the amounts are negligible. In Sweden it is a significant percentage and the wind modeled here is, for simplicity, the same type as modeled later (type 4 - full scale converter unit). The wind is added in SE3 as this area has most wind production in Sweden.
- There is too little installed capacity in NO1, so capacity (P_{Max} and M_{Base}) is increased to fulfill area production.
- Hydro in SE is not in scale with production in SE1+SE2. The production in these areas is therefore larger than in the data from Nord Pool Spot to get the share of hydro right (moved from SE3).
- As this is an aggregated model the units are quite large and to avoid generators running at 50 % or so some generators are adjusted down in size (P_{Max} and M_{Base}).
- Production in SE4 is low and to avoid low output percent and reducing size of initial generators too much, some production (262 MW) is moved from SE3 to SE4.

	Total	**Norway**	**Sweden**	**Finland**
Hydro power installed [MW]	43 602.30	26 945.60	13 956.70	2700.00
Hydro power online [MW]	11 117.24	7330.24	2887.00	900.00
Running hydro [MW]	9692.00	6403.00	2550.00	739.00
Spinning hydro reserves [MW]	1425.24	927.24	337.00	161.00

Table 24: Scenario 2 - Hydro power details.

Details of hydro power are seen above, the spinning reserves have shrunk compared to Scenario 1. Production and load data is given in "Appendix A - Production/load data".

7.5.3 *LOAD FLOW*

As the first scenario revealed the model's weaknesses there are no surprise that this case does not reflect the correct load flow either. However, not much attention is put on the load flow as the dynamic simulations are the important part of this thesis.

A graphical view of the actual scenario load flow and the simulated load flow can be seen in "Appendix B - Load flow data".

7.5.4 *DYNAMIC SIMULATIONS*

The same disturbance as applied in scenario 1 is tested. The inertia in this scenario is found to be

$$\sum_{i=1}^{n} H_i M_{BASE,i} = 135.13\ GWs$$

7.5.4.1 Permanent droop as for scenario 1

With all governor settings equal to scenario 1, the frequency bias for scenario 2 is

$$\sum_{i=1}^{n} \frac{P_{MAX,i}}{\rho_{effective,i} * 50} = 2068\ MW/HZ$$

Hence the frequency bias is much lower than for scenario 1. The response of scenario 1 versus scenario 2 can be seen in Figure 45. As expected the steady state frequency is low, as the permanent droop is not adjusted.

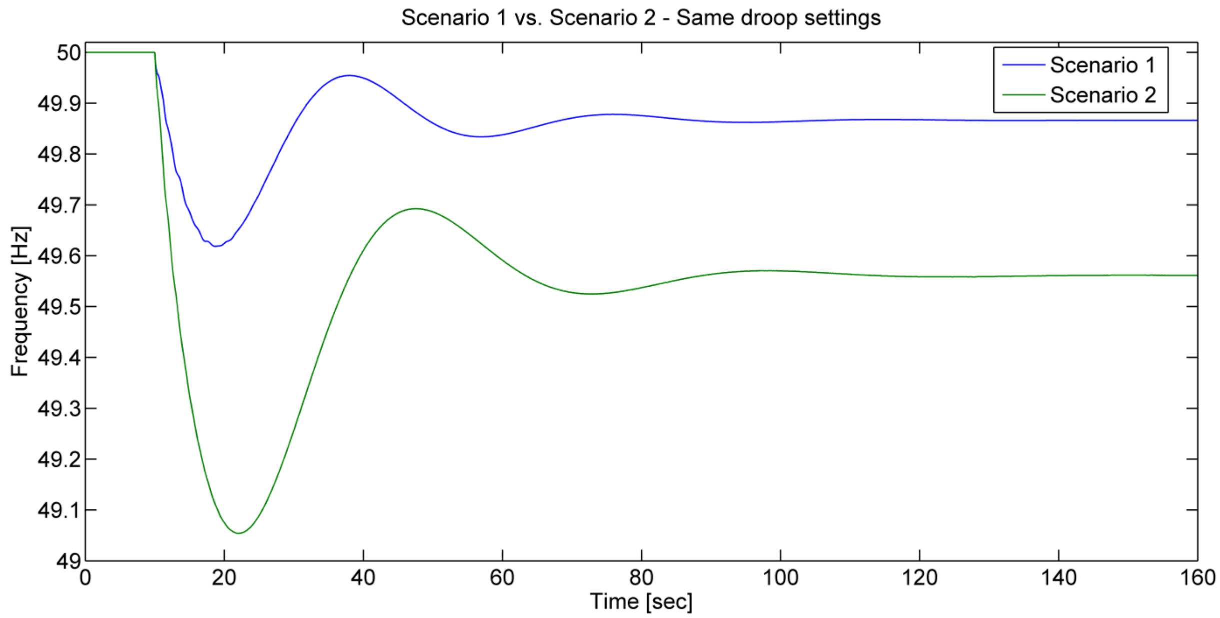

Figure 45: Scenario 1 vs. scenario 2 - Frequency response with all settings kept equal.

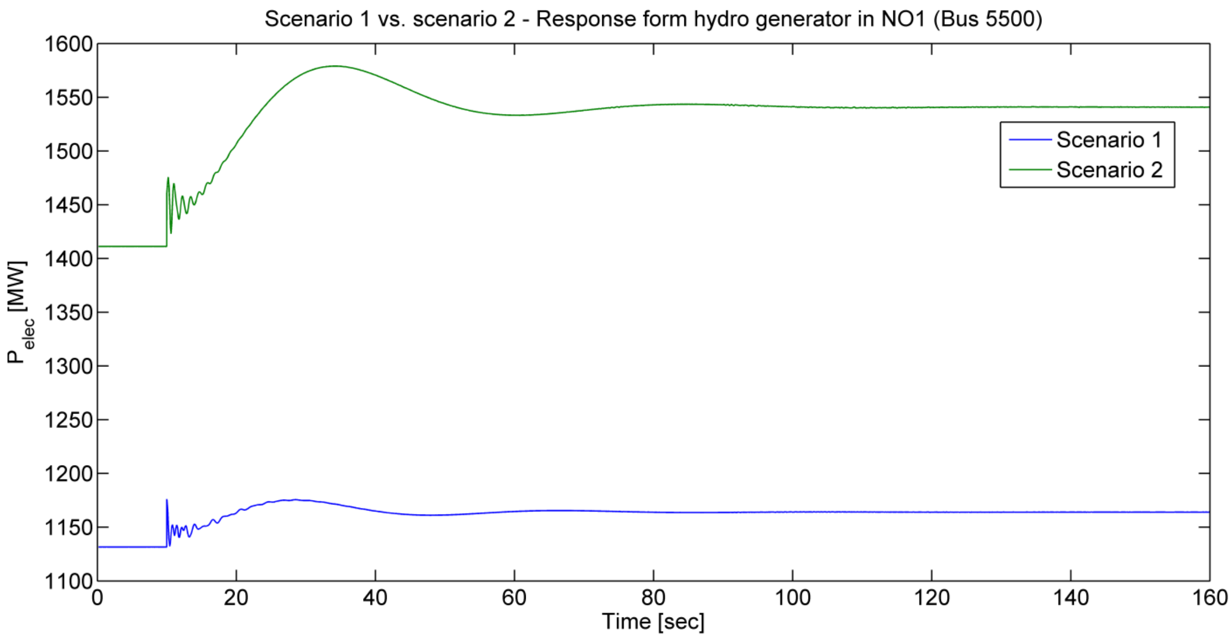

Figure 46: Scenario 1 vs. scenario 2 - P_{elec} for hydro generator in NO1

Response from a hydro governor in Norway can be seen in Figure 46. The frequency deviation is much bigger in this scenario so the need for frequency response has increased.

7.5.4.2 Distribution of the inertia

As seen in the production data there are not on-line generators on all buses in this scenario. To check the importance of inertia distribution an attempt to adjust this is tested. In NO5/NO2 there is only production on two buses initially (unit 1 on bus 6100 and 5400). In this simulation the production is divided between all buses in this area (5300, 5400, 5600, 6000 and 6100). In this case the H-constants and M_{base} values are adjusted such that precisely the same amount of inertia and FCR are present in the system. In SE and FI there are online generators on all buses where possible, so no modifications are done here.

	R – [MW/Hz]	Inertia [Gws]	Nadir [Hz]	Time to nadir, t_{min} [sec]	Δf_{ss} [Hz]
Original with original droop	2068	135.13	49.0541	22.0	0.4381
Distributed inertia	2068	135.13	49.0577	22.0	0.4381

Table 25: Result of distributing production on all buses in NO2/NO5 - Frequency indicators.

The influence on the nadir is not very significant, but a little impact is seen when distributing the inertia. Probably this will give a more significant result in a real model.

7.5.4.3 Initial frequency 49.9 Hz

In order to check whether the FCR-D requirement is fulfilled the outage is simulated at 49.9 Hz.

Droop settings	R – [MW/Hz]	Nadir [Hz]	Time to nadir, t_{min} [sec]	Δf_{ss} [Hz]	f_{ss} [Hz]	Activated after 5 sec
Original droop	2071	48.956	22.0	0.44	49.46	37.6%
8 %	3338	48.981	21.4	0.29	49.61	36.7%
4 %	6676	48.998	20.8	0.15	49.75	35.8%

Table 26: Scenario 2 - 49.9 Hz - Frequency indicators and key data changed droop settings.

With original droop settings the transient response is below the limit of 49.0 Hz and the steady state frequency is below the limit of 49.5 Hz. The calculated R is not above 3000 MW/Hz. To fulfill this requirement a permanent droop setting of 8 % is satisfactory. These settings do improve the nadir slightly, and the steady state frequency is increased to a satisfactory level. The droop is further lowered to 4 % but this does not raise the nadir enough either. However, a reduction to 4 % droop is probably too low as an average and in reality more generators would probably be turned on.

When looking at the FCR-D requirements regarding activation amount and time, Figure 47 shows that neither of the responses do fulfill the 50 % activation after five seconds (15 seconds on the graph). The 30 seconds requirement is fulfilled, but not at steady state. Note that the last column in Table 26 is additional output after five seconds divided by total additional output, and the decreasing percentage is because the total output is larger with 4 % droop than the original droop, but the response after 5 seconds is not changed in the same degree (e.g. with original droop settings the increase in hydro production is 1004 MW and after 5 seconds 378 MW is activated, while with a droop setting of 4 % the total response is 1066 MW, where 382 is activated after 5 seconds). Changing of the droop affects mostly the total response, in other words.

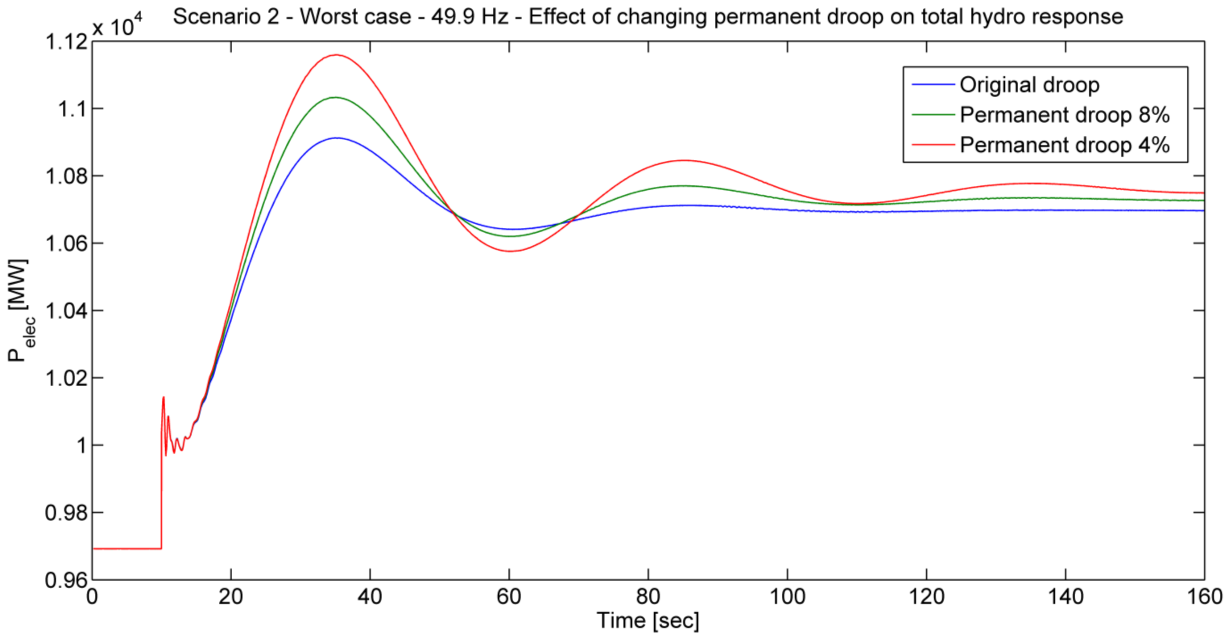

Figure 47: Scenario 2 - 49.9 Hz - Total hydro response with changed droop settings.

The conclusion is that it is not satisfactory only to adjust the permanent droop in this case. This means the inertia is a problem. An attempt to turn on more hydro power capacity at a lower output is done, and the total hydro response is seen in Figure 48. The permanent droop is kept fixed at 8 %. This will increase both the inertia and the FCR in the system as seen in Table 27.

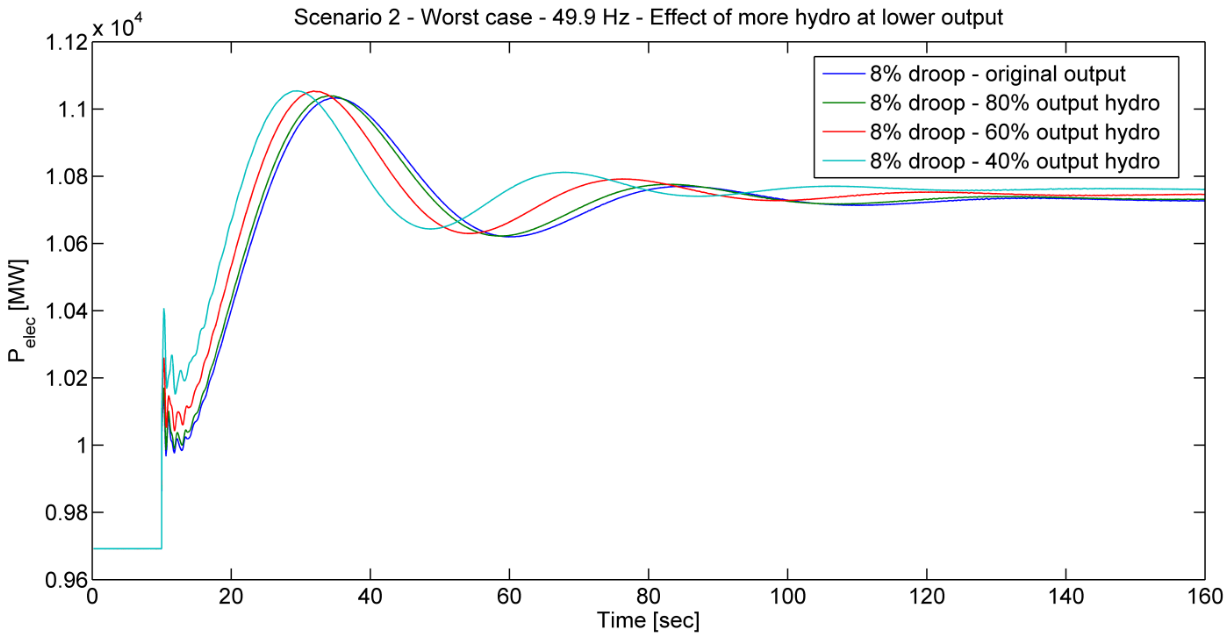

Figure 48: Scenario 2 - 49.9 Hz - Total hydro response - increased hydro at lower output.

Hydro output	Inertia [GWs]	R [MW/Hz]	Nadir [Hz]	Time to nadir, t_{min} [sec]	Δf_{ss} [Hz]	f_{ss} [Hz]	Activated after 5 sec
80%	138.8	3606	49.01	20.9	0.27	49.63	38.7%
60%	153.1	4661	49.134	19.9	0.22	49.68	45.7%
40%	185.9	7015	49.30	18.6	0.15	49.75	54.6%

Table 27: Scenario 2 - 49.9 Hz - Frequency indicators and key data for more hydro online.

As can be seen in Figure 48 the response from the hydro generators has improved. However, the 5 seconds FCR-D requirement is only fulfilled for 40 % output on all hydro generators, which is quite unrealistic. Regarding the 100 % activation at 30 seconds it is satisfied, but not at steady state.

7.6 Scenario 3

Summer day 2020	NO	SE	FI	Total
Consumption [MW]	10 000	10 500	6200	26 700
Production [MW]	6067	10 900	5694	22 661

Table 28: Scenario 3 - Data for production levels given from Statnett [27]. Loads are adjusted correspondingly.

This is a future 2020 scenario where scenario 2 is used as a basis, but high import on all Norwegian HVDC links is included. In 2020 it is expected that the HVDC links to both Germany and Great Britain are in operation. A new line in the middle of Norway is also included, from NO5 to NO3. This is a 420 kV line with a proposed rating of 1500 MVA. Estimates of production are given from Statnett's "worst case scenario" [27] and load has been increased correspondingly. The production is slightly increased compared to scenario 2. This is not as expected and should probably have been adjusted, but for simplicity the data given was used. Three versions of this scenario will be tested.

Assumptions/modifications for Scenario 3:

- All modeled wind is of full converter type.
- As the focus is on Norway, high import is included on the Norwegian cables, while import/export in Finland and Sweden are more or less unchanged from Scenario 2.
- The new Norwegian line from NO5 to NO3 is from a 300 kV to a 420 kV bus. This is because the voltage levels are not up to date in the model and a transformer is needed. This is modeled similar as other transformers used in the model.
- Import level is 85 % on all Norwegian cables, meaning a total of 4420 MW import to Norway.

7.6.1 *Scenario 3a - High import and production portfolio as today*

This version introduces the high import in Norway and keeps the share of production as in Scenario 2.

	Nuclear [MW]	Hydro [MW]	Small Hydro [MW]	Pump Hydro [MW]	Thermal [MW]	Wind [MW]	Total [MW]
Norway	0	5332.64 (87.9%)	267.39 (4.4%)	-36.46 (-0.6%)	376.77 (6.2%)	127.61 (2.1%)	6067.0
Sweden	7444.4 (68.3%)	2420 .0 (22.2%)	-	-	261.6 (2.4%)	774.0 (7.1%)	10 900.0
Finland	3291.0 (57.8%)	900.0 (15.8%)	-	-	1469.0 (25.8%)	34.0 (0.6%)	5694.0
Total	10 735.4 (47.2%)	8652.64 (38%)	267.39 (1.8%)	-	2106.9 (9%)	935.61 (4.1%)	22 661

Table 29: Scenario 3a - Share of production (approximately similar to scenario 2).

Assumptions/modifications for Scenario 3a:

- All new cables are modeled as negative loads. NSN at bus 6000 and Nordlink at bus 5600, while Skagerak 4 is included in the already existing load at bus 5603 (Skagerak 1-3).
- There is no division between small scale hydro and hydro, all hydro production is lumped into one part.
- 538 MW is moved from SE3 to SE2/SE1 to fulfill the amount of hydro power.
- 414 MW is moved from SE3 to SE4 to avoid running on low output and decrease generator too much.
- WTs are build in SE3 (as in scenario 2) and makes up 4 % of total system production.

Load flow and production data for this scenario is left out as it uses scenario 2 as a basis.

The SNSP for this scenario is

$$SNSP = \frac{P_{wind} + P_{HVDC(import)}}{P_{load} + P_{HVDC(export)}} = 0.233 = 23.3\ \%$$

The system inertia is reduced to

$$\sum_{i=1}^{n} H_i M_{BASE,i} = 134.79\ GWs$$

and with original droop settings the frequency bias is

$$R = \sum_{i=1}^{n} \frac{P_{MAX,i}}{\rho_{Effective,i} * 50} = 1951.28\ MW/HZ$$

Hence the FCR requirement is not fulfilled with original settings. As this is a similar scenario to scenario 2, the worst case version and further investigation is left out as it is only used as a basis for scenario 3b and 3c. The comparison between scenario 2 and scenario 3a is seen in Figure 49.

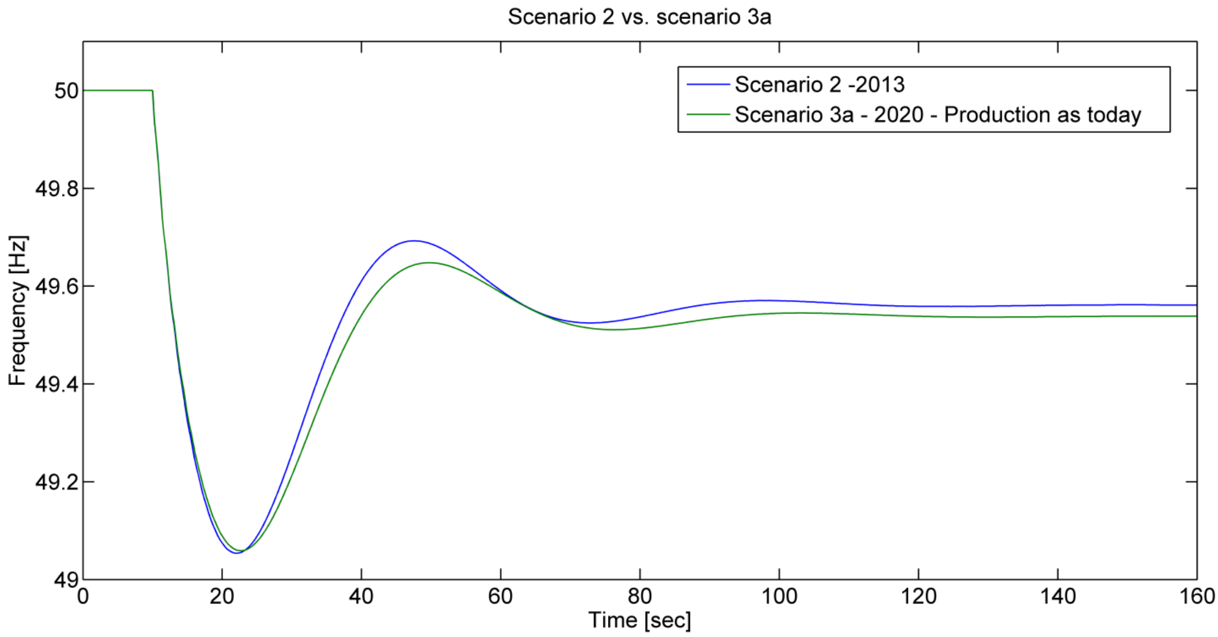

Figure 49: Scenario 2 vs. scenario 3a, both with original droop settings - Frequency.

7.6.2 *SCENARIO 3B - HIGH IMPORT AND 20 % WIND GENERATION*

This scenario combines high import in Norway and "worst case" production including a significant amount of wind power.

23.06.2013 05:00-06:00	**Nuclear [MW]**	**Hydro [MW]**	**Small Hydro [MW]**	**Thermal [MW]**	**Wind [MW]**	**Total [MW]**
Norway	0	(5000) 5701* (83.4%/93.95%)	**	(701)0* (11%/0%)	366 (6.04%)	6067
Sweden	4600 (42.2%)	3500 (32.1%)	-	300 (2.8%)	2500 (22.9%)	10900
Finland	2564 (45.0%)	346 (6.1%)	-	957 (16.8%)	1827 (32.1%)	5694
Total	7164 (31.6%)	9547* (42.1%)		1257* (5.5%)	4693 (20.7%)	22 661

Table 30: Share of production given from Statnett [27].

Assumptions/modifications for Scenario 3b:

- The thermal production in Norway is ignored and modeled as hydro power. A total of 5701 MW hydro power is therefore modeled (*). This affects the frequency bias.
- In the worst case data one version was to divide the hydro power into 2500 MW small scale hydro and 2500 MW regular hydro, but this was left out from the thesis. Small scale hydro is not handled separately (**).
- Total wind in model is 4693 MW (20.7 %).
- Division of production and load between areas is approximately as earlier
- Lumped wind generation is modeled as a wind turbine in NO3, SE3 and FI.

Load flow and production data for this scenario are left out as it is similar to scenario 2 regarding distribution of production/load.

The SNSP for scenario 3b and 3c is

$$SNSP = \frac{P_{wind} + P_{HVDC(import)}}{P_{load} + P_{HVDC(export)}} = 0.396 = 39.6\ \%$$

The system inertia is

$$\sum_{i=1}^{n} H_i M_{BASE,i} = 104.73\ GWs$$

and with original droop settings the frequency bias is

$$R = \sum_{i=1}^{n} \frac{P_{MAX,i}}{\rho_{Effective,i} * 50} = 2052.92\ MW/Hz$$

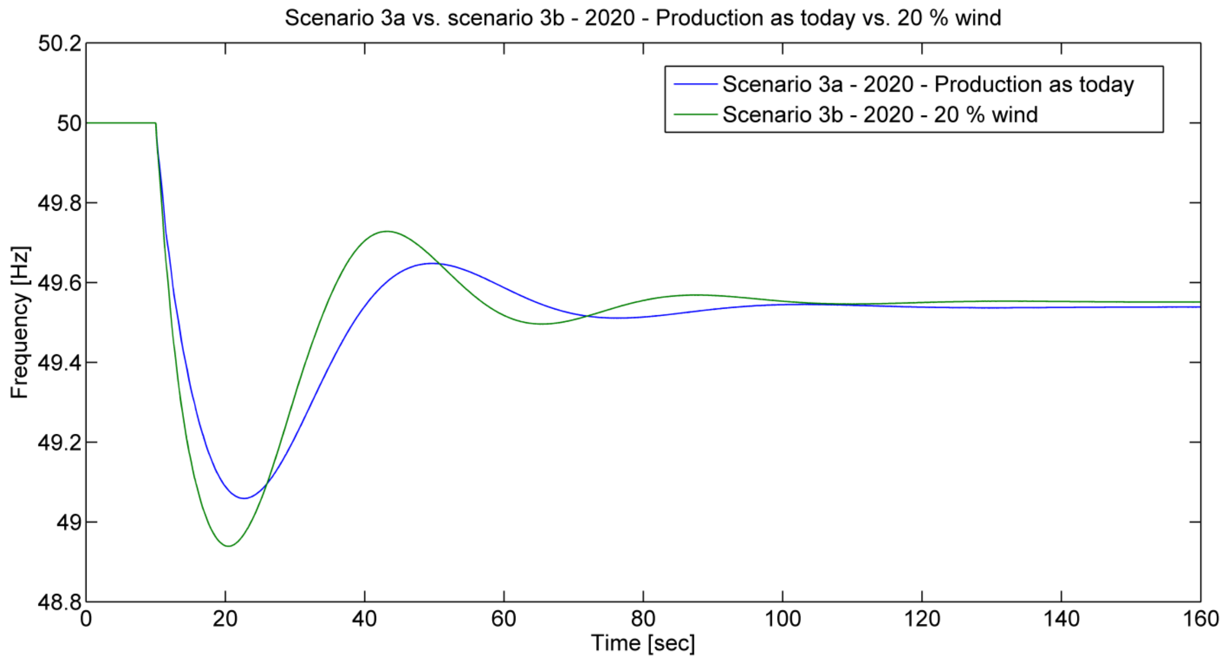

Figure 50: Scenario 3a vs. scenario 3b - Frequency.

	Inertia [GWs]	R [MW/Hz]	Nadir [Hz]	Time to nadir, t_{min} [sec]	Δf_{ss} [Hz]	f_{ss} [Hz]
Scenario 3a	134.79	1951.28	49.0593	22.7	0.461	49.539
Scenario 3b	104.73	2052.92	48.9396	20.5	0.449	49.551

Table 31: Scenario 3a vs. scenario 3b - Frequency indicators.

As expected the increased part of decoupled wind power makes the nadir lower and the ROCOF steeper. The inertia level is significantly reduced. However, when comparing Table 29 and Table 30 the share of the production "today" deviates from the worst case 2020 portfolio in several ways. In addition to the increased wind, the nuclear/other thermal part is reduced from a total 56.2 % to 37.1 %, while the hydro power has increased about 2 %. The reduced inertia is caused by wind turbines replacing rotating mass and the slightly higher frequency bias is because of the increased share of hydro. This must be taken into consideration when comparing the results.

7.6.2.1 Compensation with synthetic inertia on wind turbines

The synthetic inertia functionality is here activated for the three wind turbines modeled in SE3, FI and NO3.

Assumptions/modifications for Scenario 3c:

- Wind inertia is activated on all wind turbines simultaneously with the same values.
- As inertia is in focus here, APC is not activated.
- All parameters in WindINERTIA initially at their default value (K_{wi} = 10).

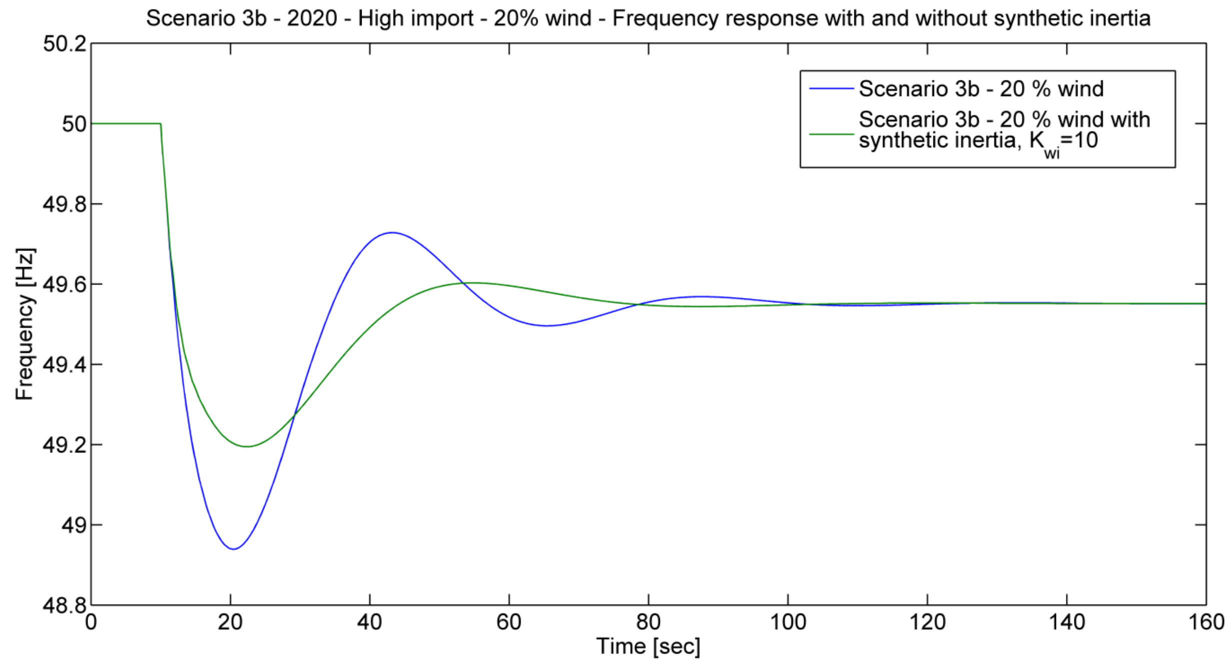

Figure 51: Scenario 3b - Frequency response with and without synthetic inertia.

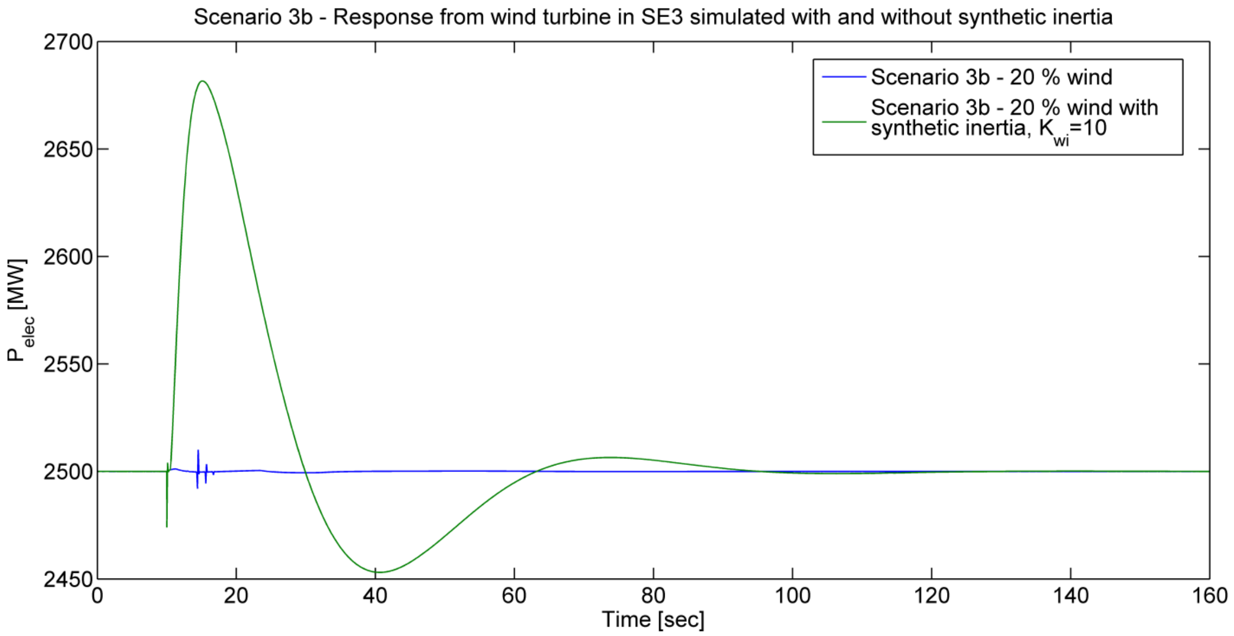

Figure 52: Scenario 3b - P_{elec} for wind turbine in SE3.

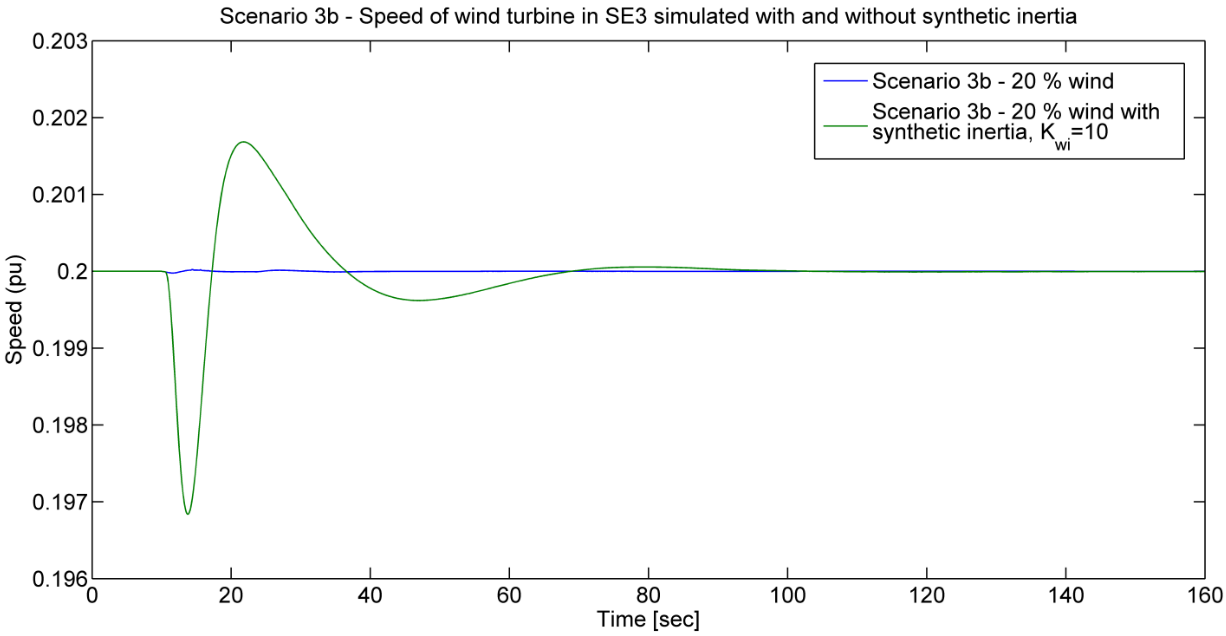

Figure 53: Scenario 3b - Speed of wind turbine in SE3 with and without synthetic inertia.

The two figures above show electrical power from the wind turbine and rotor speed. The effect of how the wind turbine decelerates and creates an increased power output, before it reaccelerates and creates a need for recovery energy can clearly be seen. The reduction in speed needed is quite small compared to the extra power output.

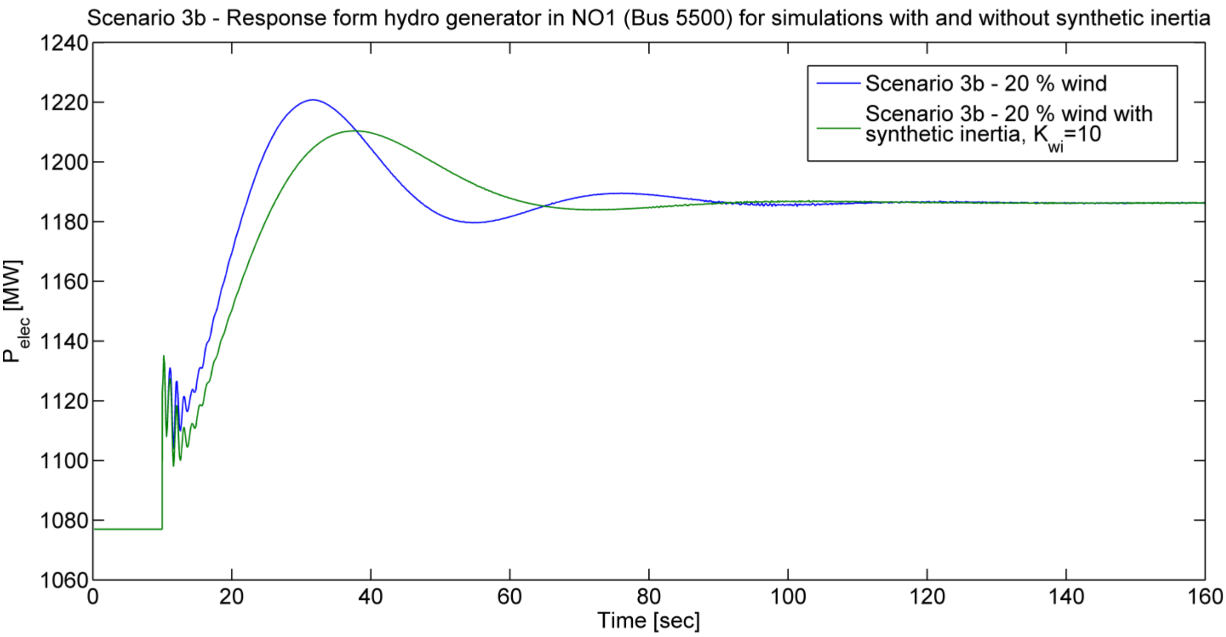

Figure 54: Scenario 3b - P_{elec} for hydro governor in NO1 with and without synthetic inertia.

Introducing synthetic inertia with default parameters is a successful way to improve the inertial response in the system. Note that the increase of inertia makes the response from hydro governors smaller and slower as seen in Figure 54. This is due to the reduced ROCOF and the raised nadir. To compare and quantify the synthetic inertia might be misleading as the units may be confusing (MWs or GW/Hz). However, a way to calculate the synthetic inertia is

$$\sum_{i=1}^{n} M_{BASE,i} * K_{wi,i} = 56\,340\ MWs\ (MW/Hz)$$

The default parameters for the WindINERTIA are mainly used throughout the thesis. Two critical parameters for the response are the gain K_{wi} and the wash out time constant T_{wowi}. These will be investigated further, by changing them from the default value while keeping all other settings unchanged.

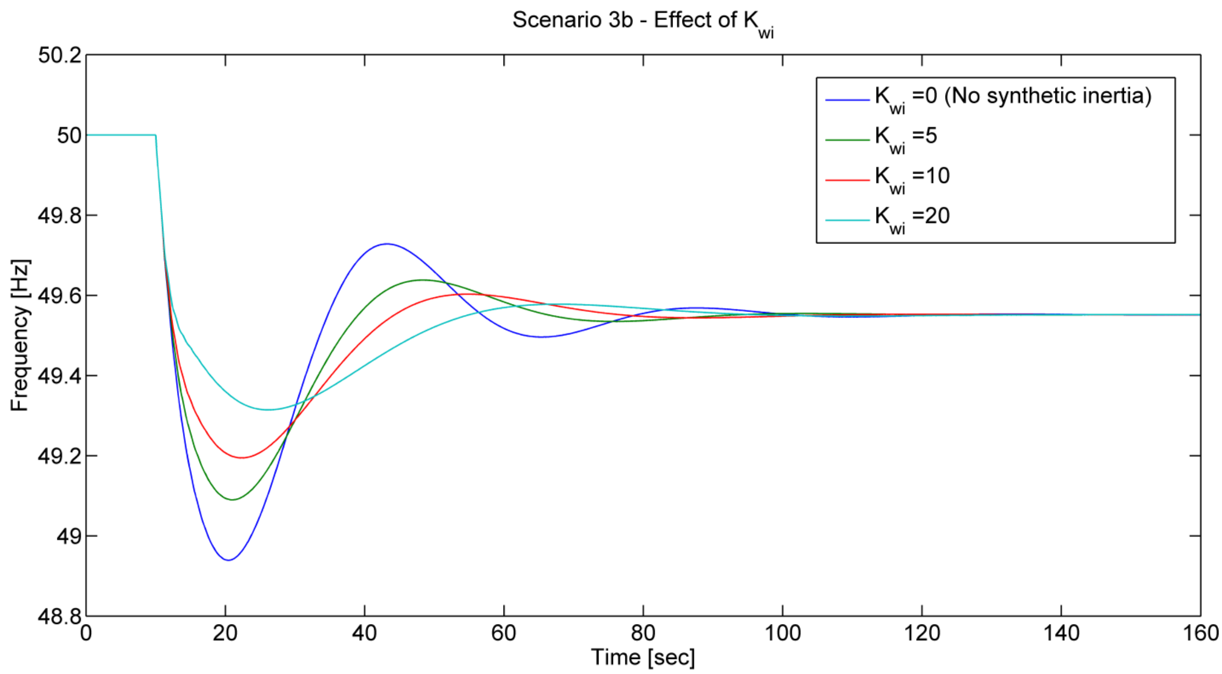

Figure 55: Scenario 3b - Varying K_{wi}, all other WindINERTIA parameters as default.

	Nadir [Hz]	Time to nadir, t_{min} [sec]
Scenario 3b – K_{wi}=0	48.9396	20.5
Scenario 3b – K_{wi}=5	49.0902	21.0
Scenario 3b – K_{wi}=10	49.1948	22.3
Scenario 3b – K_{wi}=20	49.3145	26.1

Table 32: Scenario 3b - Frequency indicators with different K_{wi}.

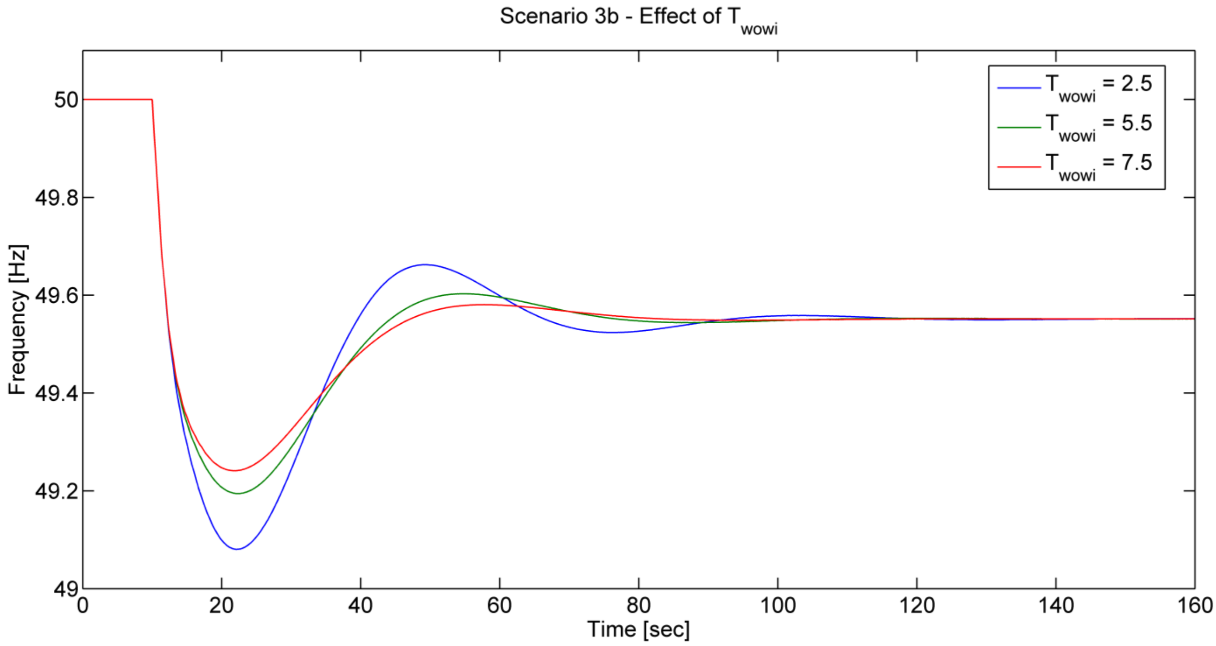

Figure 56: Scenario 3b - Varying T_{wowi}, all other parameters as default and K_{wi}=10.

	Nadir [Hz]	Time to nadir, t_{min} [sec]
Scenario 3b – T_{wowi} =2.5	49.0807	22.1
Scenario 3b – T_{wowi} =5.5	49.1948	22.3
Scenario 3b – T_{wowi} =7.5	49.2414	21.8

Table 33: Scenario 3b - Frequency indicators with different T_{wowi}.

The parameter tuning will be a trade-off between the frequency nadir and the frequency restoration time. In this case a K_{wi} = 5 is sufficient regarding the transient limit. The wash out time constant could be reduced to 2.5, if other settings are default.

7.6.2.2 Compensation adding synchronous condenser

As an option for compensation, adding a synchronous condenser will also be tested. First the original Feda condenser is added, but this is a small unit so it will not contribute much to the total inertia. However, an attempt to scale up this unit to 1000 MVA and 3000 MVA was made representing the effect of adding several or larger units. The Feda condenser has an inertia constant H=2.0, this is not changed for the other cases.

	Nadir [Hz]	Time to nadir, t_{min} [sec]
Original response	48.9396	20.5
M_{BASE} = 170 MVA (Feda)	48.9426	20.5
M_{BASE} = 1000 MVA	48.9476	20.6
M_{BASE} = 3000 MVA	48.9546	20.8

Table 34: Scenario 3b - Frequency indicators if using SC as inertia compensation.

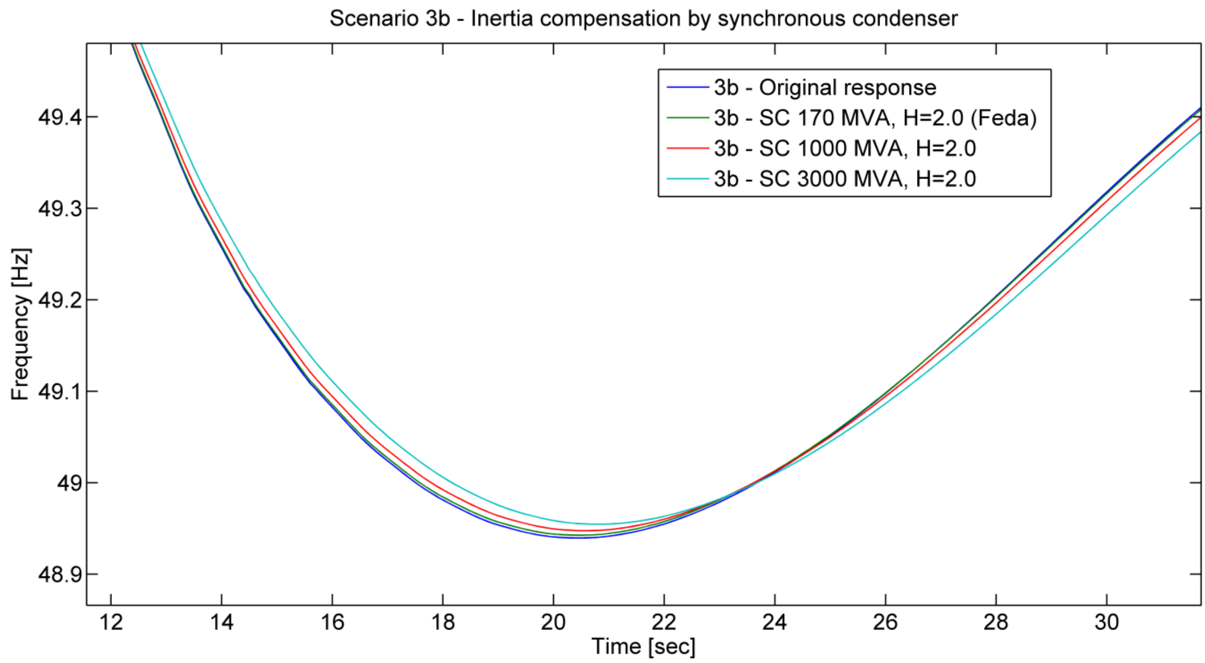

Figure 57: Effect of synchronous condensers at different ratings on the frequency nadir

As seen in Table 34 and Figure 57 the effect on the nadir is very small even when the SC is scaled up. This is due to the small inertia constant.

7.6.2.3 Initial frequency at 49.9 Hz

When running the outage from 49.9 Hz with original droop settings the nadir is lower than the transient limit of 49.0 Hz and the steady state frequency is below 45.5 Hz. As this is a light load scenario the permanent droop is attempted adjusted to 8 %. This does not fulfill the transient frequency limit but the steady state frequency is now above 45.5 Hz. 50 % of the response is not activated 5 seconds after the disturbance in any of the cases.

Introducing synthetic inertia to raise the nadir is successful, K_{wi}=5 and K_{wi}=10 are both sufficient to get a nadir higher than the transient limit. However, the response from hydro units gets even slower as the frequency falls slower and FCR requirements are even further away to be fulfilled after 5 and 30 seconds. Note that the droop on both synthetic inertia cases was left at 8 %.

Settings	R – [MW/Hz]	Nadir [Hz]	Time to nadir, t_{min} [sec]	Δf_{ss} [Hz]	f_{ss} [Hz]
Original droop	2057.04	48.8417	20.5	0.4478	49.4522
8 % droop	3248.15	48.8640	19.9	0.3027	49.5973
Synthetic Inertia, K_{wi} = 10	3248.15	49.1200	21.0	0.3007	49.5993
Synthetic Inertia, K_{wi} = 5	3248.15	49.0143	20.1	0.2987	49.6013

Table 35: Scenario 3b – 49.9 Hz - Frequency indicators.

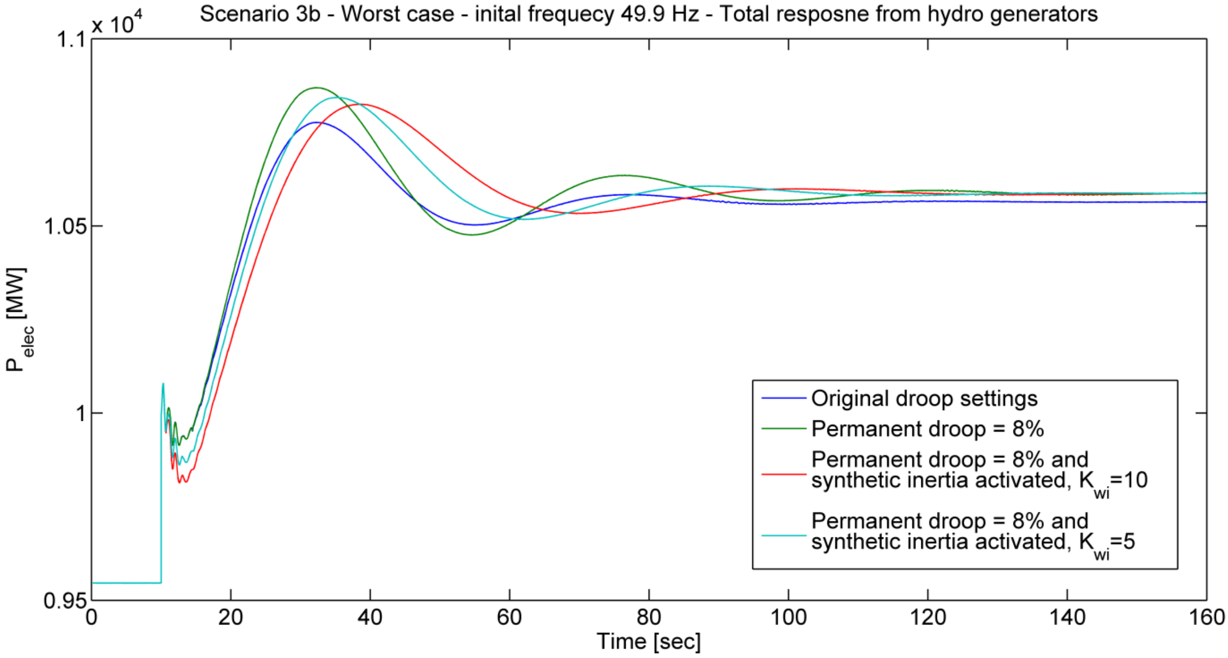

Figure 58: Scenario 3b - 49.9 Hz - Total hydro response with 8 % droop and synthetic inertia.

7.6.3 *Scenario 3c - High import and 30 % synthetic inertia on wind and VSC HVDC*

This scenario combines high import in Norway and the possibility of synthetic inertia on both wind generation and VSC HVDC cables. This means 30 % of the load is covered by wind or VSC HVDC and the scenario is tested with and without synthetic inertia.

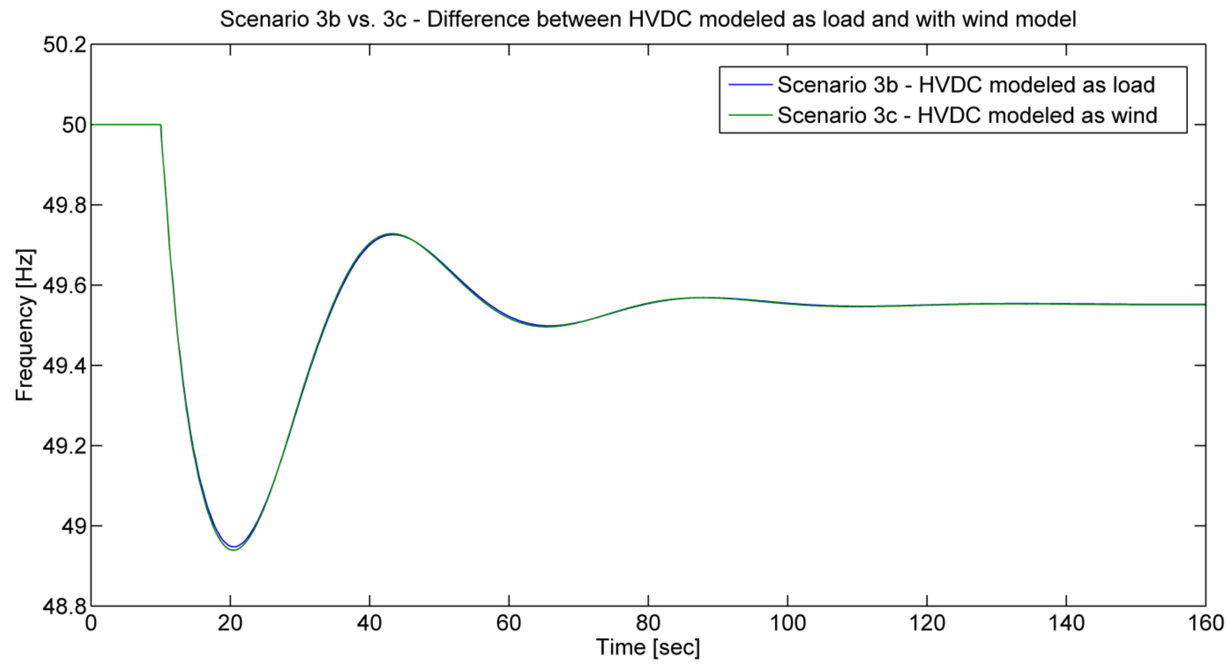

Figure 59: Scenario 3b vs. 3c - Frequency - HVDC cables modeled as loads vs. wind models.

The HVDC-cables are previous modeled as negative load, but now they are replaced by the wind turbine model. As can be seen is Figure 59, the change from load to wind model does not affect the frequency response significantly as neither of them contribute to inertia. The small difference might be because of load response. Elsewhere the scenario is similar to 3b.

The frequency response with synthetic inertia on as much as 4296 MW (5634.6 MVA) wind capacity and 2975 MW (3576 MVA) HVDC cables are shown in Figure 60.

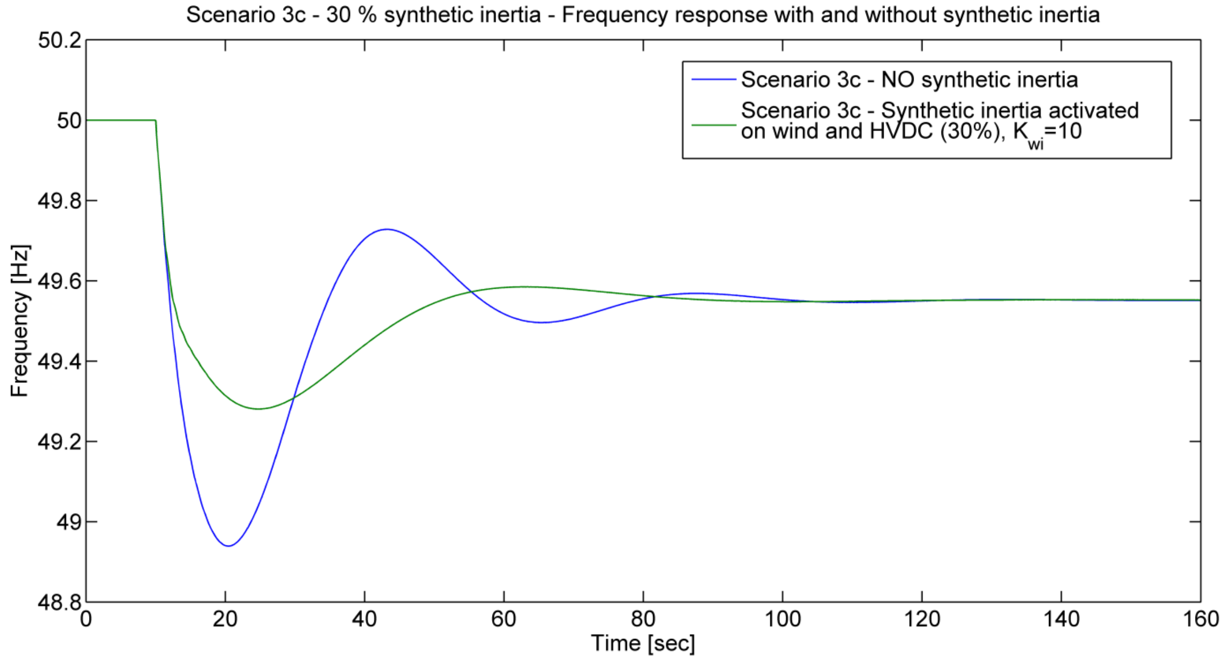

Figure 60: Scenario 3c - Frequency response with and without synthetic inertia.

	Nadir [Hz]	Time to nadir, t_{min} [sec]
Original droop settings	48.9480	20.5
With synthetic inertia, K_{wi}=10	49.2808	28.4

Table 36: Scenario 3c -Frequency indicators.

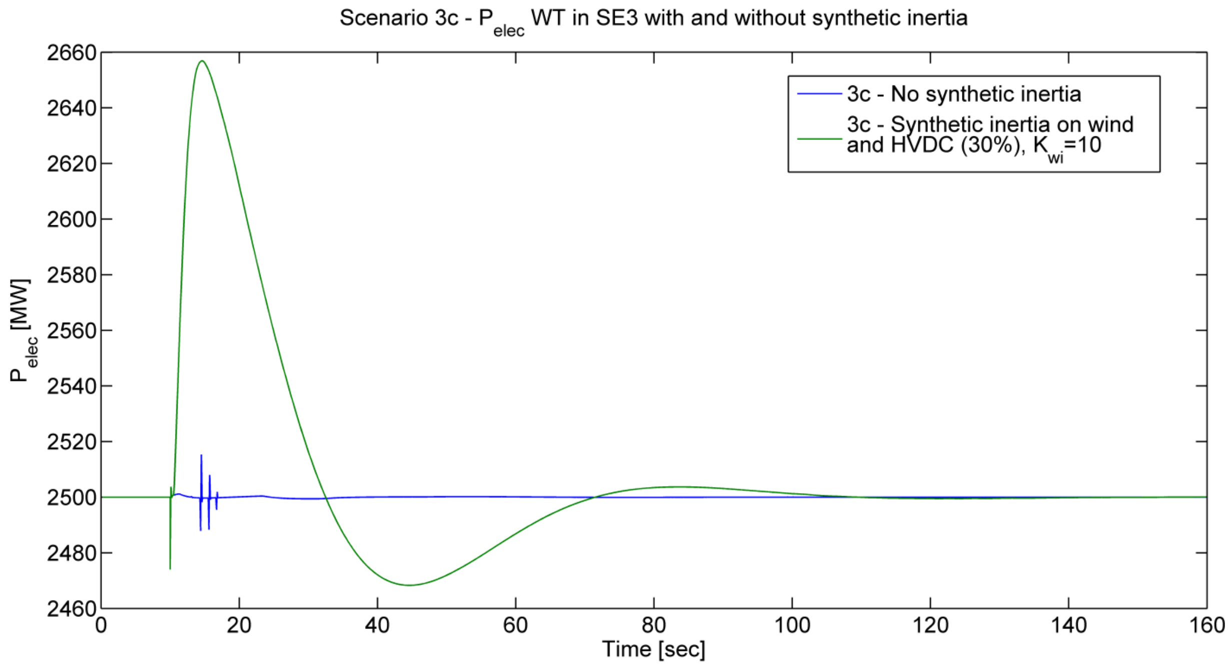

Figure 61: Scenario 3c - P_{elec} for wind turbine in SE3.

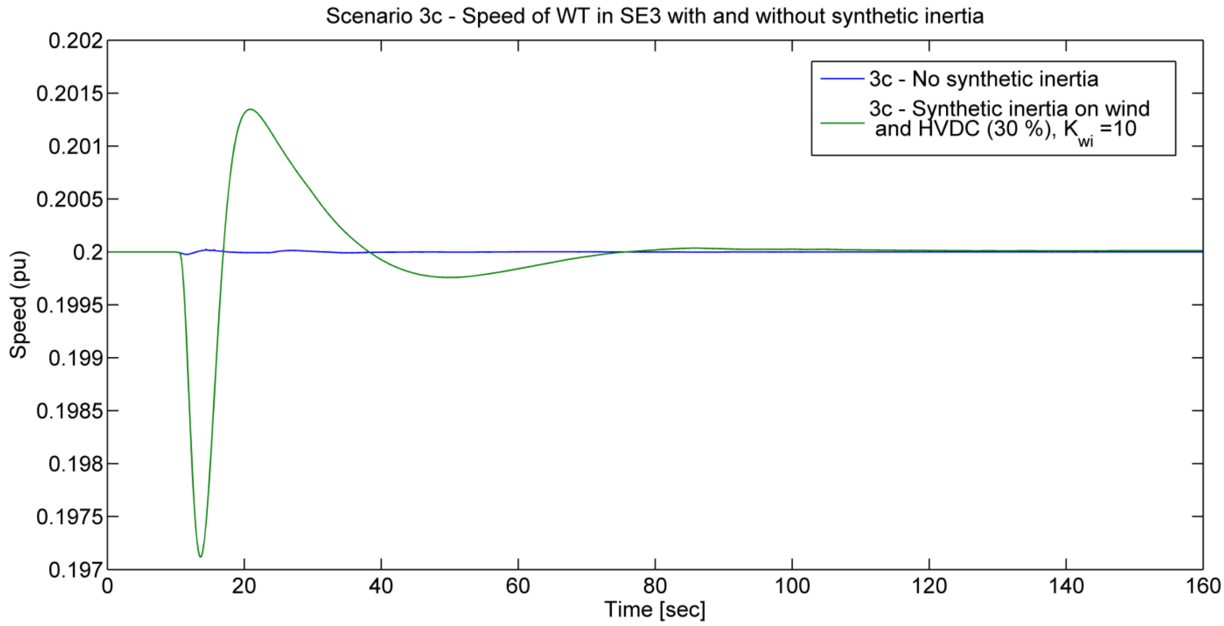

Figure 62: Scenario 3c - Speed of wind turbine in SE3.

When comparing Figure 61 and Figure 62 with Figure 52 and Figure 53 respectively, it is seen that the additional power output and speed reduction are lower in 3c than in 3b. This is because the total synthetic inertia is increased and therefore the contribution from each unit is reduced.

Total synthetic inertia available

$$\sum_{i=1}^{n} M_{BASE,i} * K_{wi,i} = 92\,1660\ MWs\ (MW/Hz)$$

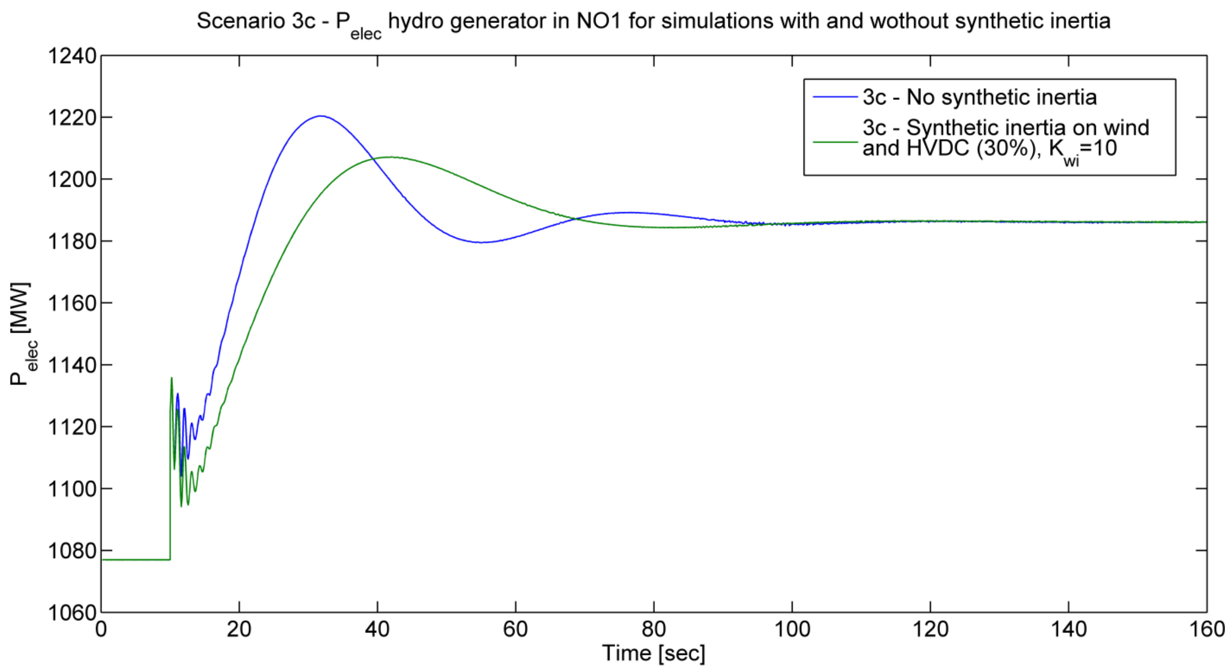

Figure 63: Scenario 3c - P_{elec} hydro governor in NO1 with and without synthetic inertia.

As the total inertia is bigger this makes the response from the hydro units slower (Figure 63).

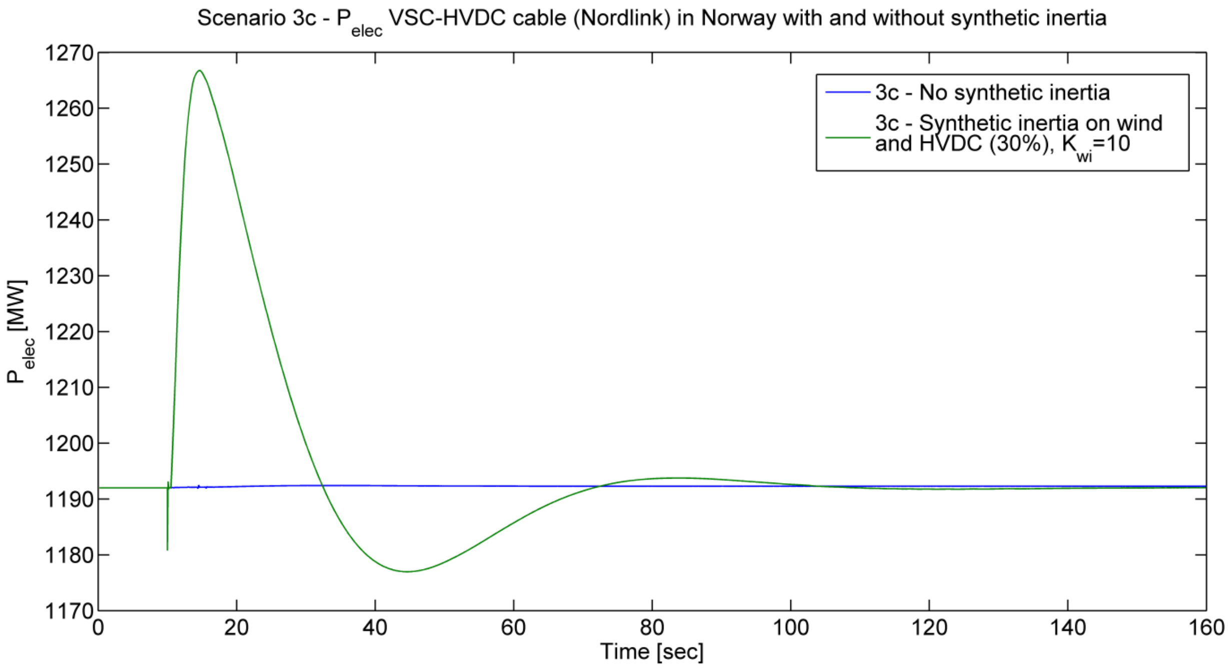

Figure 64: Scenario 3c - P_{elec} VSC HVDC cable Nordlink in Norway.

The drawback using the wind model for VSC HVDC inertia emulation is that the response is not correct. There is no need for recovery period using a VSC HVDC cable for inertia response like it is for the wind turbine that actually slows down and then speeds up again. This means the area below the blue line and above the green line between 35 and 70 seconds in Figure 64 is incorrect for a VSC HVDC cable. The connecting country can be assumed “unlimited”, hence there is no need to recover this energy. The only limitation is the capacity of the cable, meaning if the import is already 100 % there is not possible to contribute with inertia response unless the cable approves it.

In this case the cable is modeled as 85 % of the original size of the cables (e.g. Nordlink 1190 MW of 1400 MW) and then operated at rated capacity. The limit for power increase is set to 10 % of rated, meaning there is still a margin left before the maximum capacity is reached.

8 DISCUSSION

8.1 THE NORDIC44 MODEL

As pointed out, several weaknesses of the Nordic44 model have been found. Already when distributing production and load in the model, inconsistency regarding model areas was revealed. Northern parts of Sweden and southern Norway need a better representation. There are also some transmission lines missing. In addition the voltage levels and capacities on lines need to be updated. The absence of correct power flow data and voltage levels might affect the dynamic results.

Chapter 7.4.3 already discusses some of the findings from the load flow. The load flow did not end up like it should according to the Nord Pool Data. Internal flow in Norway and distribution of the flow between Norway and Sweden were especially failing. As the overloaded branches were handled by reducing line impedances a closer look should be given on the line impedances and ratings in the model. The incorrect load flow is not optimal; however, the load flow is affecting, but not crucial for the further work. The purpose of this thesis is not to change or improve the model and this is left out. What is important to note is that this might affect the dynamic results.

When running dynamic simulations the biggest problem turned out to be the voltage dependence of the load. Initially running with I/Y/P (current, admittance, power) as 60/40/0 was attempted, as this was used in previous simulations. The response was extremely slow so this was reduced to 15/15/70 and further to 10/10/80. First at these settings it was possible to get a fast enough frequency response compared to the real response.

Statnett assumes 40/40/20 (I/Y/P), Svenska Kraftnät are using 0/40/60 and Fingrid 40/25/35 meaning there are differences in the load modeling between the different system operators in the Nordic System. One reason might be that a given ZIP representation's load response is not valid for the whole timescale, and therefore it might be fitted for the purpose of the analysis [63]. Compared to the values used by the Nordic TSOs the deviation from the ones used in this thesis is large. This indicates that the voltage regulation in the model is not sufficient and this is most likely another weakness in the model. Regardless of this, it is worth to mark as it affects considerably, and since load modeling is a topic under investigation in Statnett.

The other dynamic models (except the PSSs) are not changed, so there might be data in the generator or exciter dynamic models that are not properly tuned and affect the response. This is assumed out of scope of this thesis to investigate.

8.2 ASSUMPTIONS

Several assumptions have been taken in the modeling, and some of them might affect the result and need a discussion.

There was no division between nuclear and other thermal units when modeling. In Sweden and Finland the inertia constants of the GENROU-models representing these units varies between 4.82 and 7. The highest ones belong to the nuclear units, while the smaller ones belong to other thermal units. If the amounts of nuclear and other thermal units had been handled separately the inertia level would be different. In this thesis they were lumped together and distributed regardless of the inertia constants. The right thing to do would have been to define the units in SE3, SE4 and FI as nuclear or other thermal units from the very beginning.

The same applies to some degree for hydro power in Norway. Here small scale hydro is not divided from conventional hydro. The H-constants for hydro in Norway vary from 3.0 to 4.10, while in Finland and Sweden they are between 3.20 and 4.74. In scenario 1 and 2, the amounts of small scale hydro are negligible, while in the future scenario it would affect the outcome. As the inertia constants of small scale hydro is lower (e.g. H=1 is proposed in the worst case data given form Statnett [27]) this would have decreased the inertia level further. An average H constant of 2.7 is calculated for Norwegian hydro power plants [64], meaning values in the model are high compared to this. Regarding the inertia findings, this might be a source of error.

Another factor that should have been handled different is the output of the different generators. A basis of all units was 90 % output of P_{Max}, however, to avoid changing P_{Max} and M_{Base} for all generators in all scenarios a variation from 79-93 % is seen. In retrospect it is clear that the output levels should have been more consistent throughout the scenarios.

Sometimes production is moved from one model area to another due to mismatch between the sizes of the hydro production and the area production (as explained in 6.2.3 for Sweden). Production is also moved to avoid shrinking or expanding generators so much that dynamic data must be changed to get a valid initialization. These procedures should also have been more consistent.

Since the levels of production are not consistent throughout the scenarios, it must be taken into account as an uncertainty when comparing the scenarios. This since the size of the unit and the output will affect the inertia, and for hydro units the reserves. In Statnett's mentioned worst case data, hydro generators were assumed 80 % and all other 90 % output of P_{Max}, but as this data was received late in the thesis it is not used strictly in the simulations.

8.3 SCENARIO 1

8.3.1 *THE ORIGINAL RESPONSE*

As this was a planned outage of the nuclear plant in Sweden the frequency was initially adjusted artificially high prior to the event. The minute before the outage the frequency had a maximum of 50.156 Hz and was 50.13 Hz in the moment the outage happened. This means the frequency "only" dipped down to 49.736 Hz in real life, versus 49.618 Hz in the offset version starting at 50 Hz.

However, 49.736 Hz is a low frequency and there might have been HVDC emergency power or load shedding below 49.9 Hz. Also, settings on hydro governors in SE might change after such an outage; the proportional gain (K_p) and the droop will most likely change while the integral time remains constant. In addition some generators in Denmark and Finland do have different settings when operating below 49.9 [58, 65]. All these factors might have influenced the response, and is something not included in the PSS®E model. For this reason it might not be possible to obtain the correct response without including more advanced system protection and settings in the model. However, after adjusting the voltage dependence of the load, the simulated response did not end up far away from the measured response. The assumption to change the load representation must be taken in consideration together with other settings and simplifications that might be exaggerated to obtain the correct response.

8.3.2 *THE SIMULATED RESPONSE*

The simulated response is quite close to the measured one. As mentioned in the previous paragraph, all assumptions must be taken into consideration.

The HYGOV-parameters needed to tune the response to include quite high permanent droop values (0.145 and 0.10 against 0.06), a relatively high transient droop (1.6 against 0.4), a low governor time constant (1.3 sec versus 5 seconds) and a high water time constant (2 seconds versus 1 second); all compared to the initial Nordic44 values. The two last ones are most likely responsible for the transient character of the response.

Another uncertainty is the amount of inertia present in the system. To read this graphical from the measured response was difficult, as shown in Figure 39 when getting two different values from just a slightly different slope. The value in the model is lower than both obtained from the measured. As mentioned, H-constants in the Nordic44 are not changed and are higher than the calculated average. Also, as voltage dependence affects the initial slope of the response, it might be a coincidence that this slope is pretty close the measured one.

As the advanced settings mentioned above (HVDC emergency power, parameter change etc.) are not included, the results from the analyses might be a bit pessimistic regarding the nadir.

8.4 SCENARIO 2

This is a scenario with low load and production where inertia and FCR are more interesting. The inertia is significantly decreased compared to the first scenario. When running with the same settings and the same outage the steady state frequency is low, but above the limit of 45.5 Hz. The nadir is 49.05 Hz and just above the transient limit. As this is a 1110 MW outage and the DI is 1400 MW, the frequency gets sensational low taking into account that it should be able to handle a 1400 MW outage.

Since this is a low production/load scenario, it would have been natural to reduce the droop (e.g. to 6-8 %) since certain volumes of FCR-N and FCR-D are required. In this thesis the HYGOV model is used and only the permanent droop is changed after the tuning in scenario 1. The other parameters could have been changed as well, but this is left out. For modern PI or PID regulators this is different, as the gain (K_p) in most cases is possible to adjust and enables more flexibility.

Since frequency is allowed to be between 49.9 Hz and 50.1 Hz during normal operation, the outage can happen on an initial frequency of 49.9 Hz. This is representing a worst case scenario. When running this scenario with original droop settings, the nadir gets lower than 49.0 Hz and the steady state frequency is not sufficiently high. The FCR-D requirement of 3000 MW/Hz is not fulfilled. As the permanent droop is high, a reduction is natural to attempt. When decreasing the droop to 8 % (for all countries) the calculated frequency bias gets higher than the FCR-D requirement of 3000 MW/Hz. Running a simulation with these settings also improves the nadir somewhat, but not above the transient limit. The steady state frequency gets above 49.5 Hz. A further reduction of the permanent droop to 4 % is also tried but the nadir is still not above the transient limit. A reduction to 4 % is a large change, but not improbable; however in practice other measures would be done, like turning on more hydro power. As the droop does not increase the nadir satisfactorily, inertia seems to be a problem in this scenario.

An attempt to turn on more hydro capacity was tested. The way this was done was to increase P_{Max} and M_{Base} on already online units, such that their output was 80 %, 60 % and 40 % of P_{Max}

respectively in different simulations. By doing this both the inertia and FCR will increase. The effect will be similar to turning on various amounts of hydro units at low (0-30 %) output, keeping the already online one at the initial output level. For simplicity, the first option was implemented. The total response from the hydro units improved, as well as the nadir. The five second requirement was first fulfilled when hydro generators were running at 40 % output of P_{Max}. This is remarkable and not a realistic operational situation. This requirement appears to be very strict in these simulations and probably this finding is not representative.

8.5 SCENARIO 3

This scenario includes high import, as 85 % of total import capacity is assumed (4420 MW). This represents some cables having 100 % import, while others lower depending on prices. However the scenario is a worst case representation and would probably never occur due to price mechanisms. Flows and production will be decided by prices. In the case of almost maximum import, the prices are likely to be high in Norway, which are seldom the case in a low load scenario. However, to illustrate a critical scenario the logical prices are ignored.

8.5.1 *3A - 2020 WITH PRODUCTION AS TODAY*

The production amounts are defined by the 2020 values, but the share of production is similar to the 2013 scenario. Inertia is approximately the same and there is nothing remarkable to discuss in this scenario.

8.5.2 *3B - 2020 WITH 20 % WIND PRODUCTION*

Increased levels of wind make the inertia lower. Despite of this, note that the share of hydro (and hence FCR) has increased from scenario 3a, as explained in 7.6.2.

When looking into compensation alternatives, synthetic inertia and SCs were considered. The first seemed to be the best option; however, the results are not comparable without a comment. As the total wind capacity installed with synthetic inertia was 5634 MVA against a scaled up 3000 MVA SC, the situations are not completely comparable. However, the deciding parameter is the low inertia constant (H=2) of the SC, compared to the flexible K_w used for wind inertia. The SC is primary installed for other purposes than inertia compensation, and probably that is for a reason.

Running this scenario from an initial frequency at 49.9 Hz, a worst case version is obtained. Introducing synthetic inertia did raise the nadir and decelerated the frequency drop. However, this also makes the system slower and the hydro governors respond later, so the FCR-D requirements are not successfully met.

8.5.3 *3C - 2020 WITH 30 % SYNTHETIC INERTIA*

In 3a and 3b the HVDC cables are modeled as negative loads like the original cables in the model, while in 3c they are interchanged with the wind model so they can contribute with inertia. This means more synthetic inertia available, but this scenario verifies the same as scenario 3b.

A weakness in this scenario is the use of the wind model when modeling VSC HVDC. An attempt to create a new model was done, but skipped due to time limitations. The effect of this inertia emulation is therefore not correct, and more attention should be given to this scenario.

8.6 GENERAL FCR

The division between FCR-N and FCR-D makes it somehow problematic to investigate in the same study. Normally the frequency is assumed to be 50 Hz and this makes the division between FCR-N response and FCR-D response difficult. In this thesis some of the problem was omitted by running simulations at 49.9 Hz, and mainly consider the FCR-D requirements.

When checking the FCR-D requirements several things make the study difficult. As can be seen from all hydro unit responses, the initial increase in power output during the second the fault happens, the inertial response is quite large before the power drops and then increases gradually. In theory this is also the case in a real system, but whether the shape and timescale is correct compared to a real system is unknown. For this reason the output is normally not increased by 50 % of the response five seconds after the outage.

The other factor is regarding the 30 seconds requirement. In most cases 100 % response is obtained after 30 seconds, but this is not at steady state. More often this point is on the decline from the overshoot of the power output response. This becomes a definition issue of whether the 100 % activation requirement is meant to be at steady state or not.

When looking at the response from hydro, sometimes in the thesis, one unit is considered separately while other times the total response from hydro units is depicted. The only way to control that each unit fulfill the requirement is to demand each unit to fulfill it. However, when looking at the complete system the total response requirement should still be met. A system response is slower than the response from one unit, and this makes the verifying dependent on definitions.

Sometimes the calculated frequency bias can be above 3000 MW/Hz, but still the requirements at 5 and 30 seconds are not fulfilled. The relation of these requirements is difficult to verify, as speed of response not necessary corresponds to the size of the reserve. There is ongoing work regarding the normal and disturbance part of the FCR in Statnett today. The frequency quality in the Nordic system has decreased the last years. In [19] this is qualified as duration of actual frequency outside of 49.9-50.1 Hz. This might be an indicator that the FCR-D that actually is activated below 49.9 Hz is not sufficient during major disturbances.

8.7 GENERAL INERTIA COMPENSATION

In worst case scenarios ran at 49.9 Hz the transient frequency drops below the transient limit of 49.0 Hz. Where this is the case, inertia can be assumed a problem that needs consideration. It is desired to minimize the risk of a frequency below the transient limit of 49.0 Hz. This is to avoid triggering of load shedding and other system protections. There is an ongoing discussion on whether the transient limit should be somewhat higher to leave a margin for uncertainties in the system, for instance the FCR performance.

These simulations show that synthetic inertia is a more efficient alternative of compensating than synchronous condensers. Not much literature were found on what realistic values on the gain value, K_{wi}, are, but the recommended value in the manual [59] is 10. The same applies for practical experiences with the synthetic inertia, few good studies were found. In this thesis the parameters are used as default, as they have their origin from testing. Furthermore, when using this model for VSC HVDC, some parameters (e.g. gain) could have been handled differently, as they are not restricted to the physics of a wind turbine, but a cable capacity.

The synthetic inertia is dependent on the wind conditions and this must be taken into consideration, as an assumption of constant wind speed is taken here. Obviously, if there are bad wind conditions and little wind power production, other generation types must be running and the need for more inertia might not be that inherent. Anyway, how the functionality of the synthetic inertia reduces with lower and not constant wind speed is not investigated in this work. Also to be mentioned is the operational issue present if the rotational turbine speed gets too low, the wind turbine might turn in to unstable operation.

In scenario 2 the effect of turning on more hydro power capacity on a lower output increased both inertia and FCR. This is an efficient way to increase FCR and inertia, but not a desired operational strategy. This is not optimal and energy is assumed spilled as the efficiency is reduced and it is at a lower price. Running at lower output down to 20-30 % is not mechanical possible for all generators either [19].

Pumped hydro power is not considered in these simulations but is understood as a better option. One possibility for FCR is running of a pump and a generator at the same time. The generator will use water in a reservoir for generation, while the pump will pump the water from a lower reservoir to a storage reservoir. This will increase inertia and the generator will contribute to FCR. There will be the same price of produced energy and consumed energy [19]. However, to emphasize, the economy of the compensation solution has not been studied and is out of the scope for this thesis.

Scenario 2 and 3 are both low load scenarios and in this aggregated model problems of bottlenecks are not easy to reveal. The HVDC import is concentrated in the southwest part of Norway. There is much ongoing work updating internal lines to handle the new cable capacities. However, the model is not updated regarding voltage levels, and capacities of lines remain the same throughout the simulations, except that the new line from NO5 to NO3 is included in Scenario 3. It is therefore hard to say something about bottlenecks caused by the inertia compensation and FCR from the model.

The future of wind power in Norway in the next five years is uncertain. The plans of 3000-3500 MW installed wind within 2020 might seem too optimistic. The amount of wind production to expect in Norway in 2020 will affect the level of inertia and the need for compensation. The VSC HVDC cables NordLink, NSN and NordBalt will be built, and this includes a possibility of inertia emulation. As the wind expansion is more uncertain this possibility for synthetic inertia should be taken if technology approves it.

Some kind of inertia market is not unrealistic in the future, taking into account the very varying levels of inertia experienced in this thesis. There is a need to control the inertia level in the system. In this manner there are many factors to clarify, first of all how they relate to the already existing FCR markets and the time span. The price of inertia in an eventual market is also a deciding factor for possibilities to provide inertia. Rebuilding hydro generators to be able to run in air, rebuilding nuclear generators into SCs and expanding the inertia constant of existing SCs are all alternatives mentioned, but the question of cost is relevant. Regarding synthetic inertia on wind turbines and VSC HVDC it is not known how much additional costs this implies.

9 CONCLUSION

A lot of time was used to tune the model with varying results. The load flow representation of the model needs to be updated both regarding areas, distribution of load/generators, new lines, capacity of lines and voltage levels. The PSSs was changed for this thesis, so the ones initially in the model must either be better tuned or interchanged. The most crucial for the dynamic results was the voltage dependency of the load modeling. This part needs more attention as a very different load representation was necessary than what is used by Nordic TSOs today. This is most likely a model weakness; hence the voltage regulation needs to be improved in the model. Anyway it is an important note to take that this can affect a frequency response in such a large manner.

After modifications and assumptions the simulated response from the model is not far away from the real response. However, all simplifications done must be taken into consideration when looking at the results and conclusions from the thesis. The model might get too simple to get a realistic result, as in the real response factors like HVDC emergency power, changed regulator settings below 49.9 Hz and other advanced settings might have influenced the outcome, while in the model these are not included.

As the study of FCR-N and FCR-D at the same time is difficult due to the structure, this thesis' focus is on FCR-D since an outage is tested. In this thesis only the permanent droop is adjusted, while for modern PI and PID regulators it is natural to adjust the gain value (K_p) as well. This would have affected the frequency response.

In scenario 2 and 3 the inertia levels are significantly reduced. It is critical as the nadir gets below the transient limit and inertia can be considered as a problem. This reveals that the inertia level already has been low during former operation scenarios. However, it will be further decreased if the production portfolio develops according to Statnett's data and no inertia action is taken.

Turning on more hydro power at lower output is efficient as both inertia and FCR will increase. This is not a desired way of increasing the inertia as energy is assumed spilled. Pumped hydro power is considered a better option than this, but is not considered in this thesis.

For inertia compensation synthetic inertia appeared to be a better solution than synchronous condensers. This is due to the low inertia constant of the SCs. The synthetic inertia includes more flexibility to vary its gain value, K_{wi}, and with proper tuning it will interact with rest of the power system in a successful way. For the SCs to compete with this, either large volumes or higher H-constants are needed.

Economy is not considered in this thesis. However, the future of wind power expansion in Norway is not clarified yet, while two VSC HVDC cables of significant size will be built and in operation at the end of 2020. In this thesis the synthetic inertia on VSC HVDC was not modeled and investigated in the right way, hence details from these results are not sufficient. However, according to the technology, there will most likely be possible to get inertial response from these if desired.

As the study of the FCR requirements is unclear, it is difficult to answer whether these requirements will guarantee sufficient inertia levels. The model requires large amounts of hydro capacity online to fulfill the five seconds requirement. As this appears as the most severe requirement in these simulations, this will most likely ensure that the other requirements are met. Whether this is the case in reality is more doubtingly, as there are different comprehensions of how to interpret the FCR-D requirements. The response from one hydro unit is faster than the response from the whole system, and which one to look at when verifying the requirement is uncertain.

In conclusion the definition of the FCR in the Nordic countries today is not optimal and should be given further attention, especially how to relate the output requirement based on time with the requirement of frequency bias available. Clearer definitions of the different requirements or restructuring should be considered. The need to control the amount of inertia in the system is also inherent and possibilities for inclusion of inertia in the FCR market or creation of a separate market should be investigated.

10 FURTHER WORK

There are several areas of interesting work related to this thesis. First of all the model used should be improved. Several factors mentioned in this thesis should be updated and corrected. The small size of the model is nice to make it useable, but a sufficient size and detail is needed to pick up grid related aspects like oscillations, congestions etc. Therefore a small model is nice to use in combination with a bigger one.

An interesting part is further studies of VSC HVDC inertia emulation. This might be more relevant for Norway as the future of wind is still unsure. The potential is one thing; how much can the cables deliver without sacrificing too much volume or can they handle overloading for some seconds? The power is taken from another synchronous area, how will the challenges regarding the sending country be handled?

As the HVDC cables to Germany and Great Britain are installed the DI in Norway will increase to 1400 MW and testing for a bigger outage would be reasonable in an updated version of the system.

Another study of FCR-D could be done on a more advanced model including frequency controlled emergency power on HVDC, load shedding and parameter switch for hydro power. For testing of FCR-N e.g. ramping on cables could have been used as a “disturbance”.

Inclusion of small scale hydro in the future scenario was left out in this work, but could have been investigated by reducing H-constants to a level representative for small scale hydro on half of the production. This would result in lower inertia level and more challenges for the system.

The synthetic inertia need more attention, both regarding cost, size of K_{wi} and how it works in practice. In addition possibilities of de-loading wind turbines to contribute to FCR are interesting. In this study the APC functionality was not activated, but this can either be used for deloading or, since the WindINERTIA was asymmetric, for high frequency events.

Also outages when the cable is in export operation in the future system should be tested. If this load trips (1400 MW export on cable), how will this be in a situation with mainly wind and small scale hydro production during spring flooding (run of river plants in operation)? Note that if exporting HVDC cables should provide synthetic inertia another model than the wind model is needed for this purpose.

Flywheels are another option for inertia compensation and frequency support not considered here. An investigation of the possibilities of these including simulations and economy would be interesting as these are used in the US and will be tested in Ireland in near future.

Aspects and potential covered in this thesis should also be put in relation to other measures to compensate for low inertia, and look at the cost. This is necessary to find the most socio-economic way to achieve GWs.

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Appendix A - Production/load data

Bus Number	Nordic44 Area Name	Elspot	P_{Gen} (MW)	Gen/Max [%]	P_{Max}(MW)	M_{Base} (MVA)	H-const	GWs
7100	FI1	FI1	715.33	0.79	900.00	1000.00	3.20	3200.00
7100	FI1	FI1	715.33	0.79	900.00	1000.00	3.20	3200.00
7100	FI1	FI1	715.33	0.79	900.00	1000.00	3.20	3200.00
7000	FI2	FI2	1085.50	0.93	1167.00	1278.00	5.50	7029.00
7000	FI2	FI2	1085.50	0.93	1167.00	1278.00	5.50	7029.00
7000	FI2	FI2	1085.50	0.93	1167.00	1278.00	5.50	7029.00
7000	FI2	FI2	1085.50	0.93	1167.00	1278.00	5.50	7029.00
7000	FI2	FI2	1085.50	0.93	1167.00	1278.00	5.50	7029.00
7000	FI2	FI2	1085.50	0.93	1167.00	1278.00	5.50	7029.00
7000	FI2	FI2	0.00	0.00	~~1167.00~~	~~1278.00~~	~~5.50~~	0.00
7000	FI2	FI2	0.00	0.00	~~1167.00~~	~~1278.00~~	~~5.50~~	0.00
7000	FI2	FI2	0.00	0.00	~~1167.00~~	~~1278.00~~	~~5.50~~	0.00
5500	NO1	NO1	1131.56	0.88	1280.00	1450.00	3.00	4350.00
5100	NO6	NO1	972.44	0.88	1100.00	1200.00	3.99	4784.52
5400	NO2	NO2+NO5	1305.33	0.90	1450.36	1611.52	4.10	6607.23
5400	NO2	NO2+NO5	1305.33	0.90	1450.36	1611.52	4.10	6607.23
5600	NO3	NO2+NO5	1246.00	0.90	1384.44	1538.27	3.50	5383.95
5600	NO3	NO2+NO5	1246.00	0.90	1384.44	1538.27	3.50	5383.95
6000	NO4	NO2+NO5	735.73	0.90	817.48	896.59	3.50	3138.07
6100	NO4	NO2+NO5	1329.06	0.90	1476.73	1634.96	3.00	4904.88
6100	NO4	NO2+NO5	1329.06	0.90	1476.73	1634.96	3.00	4904.88
6100	NO4	NO2+NO5	1329.06	0.90	1476.73	1634.96	3.00	4904.88
6100	NO4	NO2+NO5	1329.06	0.90	1476.73	1634.96	3.00	4904.88
6100	NO4	NO2+NO5	1329.06	0.90	1476.73	1634.96	3.00	4904.88
5300	NO5	NO2+NO5	1275.66	0.90	1417.40	1574.89	3.50	5512.12
5300	NO5	NO2+NO5	1275.66	0.90	1417.40	1574.89	3.50	5512.12
6500	NO7	NO3	814.33	0.81	1000.00	1100.00	3.56	3913.80
6500	NO7	NO3	814.33	0.81	1000.00	1100.00	3.56	3913.80
6500	NO7	NO3	814.33	0.81	1000.00	1100.00	3.56	3913.80
6500	NO7	NO3	0.00	0.00	~~1000.00~~	~~1100.00~~	~~3.56~~	0.00
6700	NO8	NO4	1753.00	0.91	1930.00	2144.44	3.59	7702.83
6700	NO8	NO4	1753.00	0.91	1930.00	2144.44	3.59	7702.83
3115	SE1	SE1	1175.00	0.90	1305.56	1450.62	4.74	6877.38
3115	SE1	SE1	1175.00	0.90	1305.56	1450.62	4.74	6877.38
3115	SE1	SE1	1175.00	0.90	1305.56	1450.62	4.74	6877.38
3249	SE1	SE2	1042.00	0.85	1230.00	1357.00	4.54	6164.85
3249	SE1	SE2	1042.00	0.85	1230.00	1357.00	4.54	6164.85
3249	SE1	SE2	1042.00	0.85	1230.00	1357.00	4.54	6164.85
3249	SE1	SE2	1042.00	0.85	1230.00	1357.00	4.54	6164.85
3249	SE1	SE2	1042.00	0.85	1230.00	1357.00	4.54	6164.85
3249	SE1	SE2	1042.00	0.85	1230.00	1357.00	4.54	6164.85
3249	SE1	SE2	1042.00	0.85	1230.00	1357.00	4.54	6164.85
3245	SE2	SE2	1000.00	0.90	1111.11	1234.57	3.30	4074.07

3000	SE3	SE3	1100.00	0.94	1167.00	1300.00	5.97	7761.00
3000	SE3	SE3	1100.00	0.94	1167.00	1300.00	5.97	7761.00
3000	SE3	SE3	0.00	0.00	~~1167.00~~	~~1300.00~~	~~5.97~~	0.00
3300	SE3	SE3	800.00	0.80	1000.00	1100.00	6.00	6600.00
3300	SE3	SE3	800.00	0.80	1000.00	1100.00	6.00	6600.00
3300	SE3	SE3	800.00	0.80	1000.00	1100.00	6.00	6600.00
3359	SE3	SE3	1110.00	0.91	1217.00	1350.00	4.82	6507.00
3359	SE3	SE3	1100.00	0.90	1217.00	1350.00	4.82	6507.00
3359	SE3	SE3	1100.00	0.90	1217.00	1350.00	4.82	6507.00
3359	SE3	SE3	0.00	0.00	~~1217.00~~	~~1350.00~~	~~4.82~~	0.00
3359	SE3	SE3	0.00	0.00	~~1217.00~~	~~1350.00~~	~~4.82~~	0.00
3359	SE3	SE3	0.00	0.00	~~1217.00~~	~~1350.00~~	~~4.82~~	0.00
8500	SE4	SE4	994.00	0.84	1183.00	1300.00	7.00	9100.00
8500	SE4	SE4	0.00	0.00	~~1183.00~~	~~1300.00~~	~~7.00~~	0.00
8500	SE4	SE4	0.00	0.00	~~1183.00~~	~~1300.00~~	~~7.00~~	0.00
8500	SE4	SE4	0.00	0.00	~~1183.00~~	~~1300.00~~	~~7.00~~	0.00
8500	SE4	SE4	0.00	0.00	~~1183.00~~	~~1300.00~~	~~7.00~~	0.00
8500	SE4	SE4	0.00	0.00	~~1183.00~~	~~1300.00~~	~~7.00~~	0.00
			52470.00		**74687.33**			**282527.79**

Table A- 1: Scenario 1 - Production data.

Bus Number	Nordic44 Area Name	Elspot	P_{load} (MW)	Q_{load} (Mvar)
7100	FI1	FI1	1431.68	200.00
7100	FI1	FI1	1431.68	200.00
7000	FI2	FI2	1593.53	70.00
7000	FI2	FI2	1593.53	70.00
7000	FI2	FI2	1593.53	70.00
7000	FI2	FI2	1593.53	70.00
7000	FI2	FI2	1593.53	70.00
7010	FI2	FI2	-1219.00	600.00
7020	FI2	FI2	343.00	-4.00
5500	NO1	NO1	2203.42	200.00
5500	NO1	NO1	2203.42	200.00
5100	NO6	NO1	1154.17	70.00
5400	NO2	NO2	1149.77	100.00
5600	NO3	NO2	674.86	125.00
5600	NO3	NO2	674.86	125.00
5610	NO3	NO2	1412.00	363.00
5620	NO3	NO2	414.00	175.00
6100	NO4	NO2	1199.76	400.00
6100	NO4	NO2	1199.76	400.00
6500	NO7	NO3	1013.00	333.00
6500	NO7	NO3	1013.00	333.00
6500	NO7	NO3	1013.00	333.00
6700	NO8	NO4	2489.00	150.00
5300	NO5	NO5	2651.00	-70.00
3115	SE1	SE1	621.00	650.00

3100	SE2	SE1	621.00	110.00
3249	SE1	SE2	2265.00	650.00
3000	SE3	SE3	1420.66	567.00
3000	SE3	SE3	1420.66	567.00
3000	SE3	SE3	1420.66	567.00
3020	SE3	SE3	1219.00	616.00
3300	SE3	SE3	1217.36	400.00
3300	SE3	SE3	1217.36	400.00
3359	SE3	SE3	1460.83	600.00
3359	SE3	SE3	1460.83	600.00
3359	SE3	SE3	1460.83	600.00
3359	SE3	SE3	1460.83	600.00
3360	SE3	SE3	-330.00	262.00
8500	SE4	SE4	1240.00	433.00
8500	SE4	SE4	1240.00	433.00
8500	SE4	SE4	1240.00	433.00
8600	SE4	SE4	546.00	10.00
8700	SE4	SE4	628.00	0.00

Table A- 2: Scenario 1 - Load data.

Bus Number	Nordic44 Area Name	Elspot	P_{Gen}(MW)	Gen/Max [%]	P_{Max}(MW)	M_{Base} (MVA)	H-const	GWs
7100	FI1	FI1	739.00	0.82	900.00	1000.00	3.20	3200.00
7100	FI1	FI1	0.00	0.00	~~900.00~~	~~1000.00~~	~~3.20~~	0.00
7100	FI1	FI1	0.00	0.00	~~900.00~~	~~1000.00~~	~~3.20~~	0.00
7000	FI2	FI2	986.25	0.85	1167.00	1278.00	5.50	7029.00
7000	FI2	FI2	986.25	0.85	1167.00	1278.00	5.50	7029.00
7000	FI2	FI2	986.25	0.85	1167.00	1278.00	5.50	7029.00
7000	FI2	FI2	986.25	0.85	1167.00	1278.00	5.50	7029.00
7000	FI2	FI2	0.00	0.00	~~1167.00~~	~~1278.00~~	~~5.50~~	0.00
7000	FI2	FI2	0.00	0.00	~~1167.00~~	~~1278.00~~	~~5.50~~	0.00
7000	FI2	FI2	0.00	0.00	~~1167.00~~	~~1278.00~~	~~5.50~~	0.00
7000	FI2	FI2	0.00	0.00	~~1167.00~~	~~1278.00~~	~~5.50~~	0.00
7000	FI2	FI2	0.00	0.00	~~1167.00~~	~~1278.00~~	~~5.50~~	0.00
5500	NO1	NO1	1411.23	0.90	1568.03	1742.26	3.00	5226.77
5100	NO6	NO1	1212.77	0.90	1347.53	1497.25	3.99	5969.69
5400	NO2	NO2+NO5	1250.00	0.86	1450.36	1611.52	4.10	6607.23
5400	NO2	NO2+NO5	0.00	0.00	~~1450.36~~	~~1611.52~~	~~4.10~~	0.00
5600	NO3	NO2+NO5	0.00	0.00	~~1384.44~~	~~1538.27~~	~~3.50~~	0.00
5600	NO3	NO2+NO5	0.00	0.00	~~1384.44~~	~~1538.27~~	~~3.50~~	0.00
6000	NO4	NO2+NO5	0.00	0.00	~~817.48~~	~~896.59~~	~~3.50~~	0.00
6100	NO4	NO2+NO5	802.00	0.86	932.56	1036.18	3.00	3108.53
6100	NO4	NO2+NO5	0.00	0.00	~~1476.73~~	~~1634.96~~	~~3.00~~	0.00
6100	NO4	NO2+NO5	0.00	0.00	~~1476.73~~	~~1634.96~~	~~3.00~~	0.00
6100	NO4	NO2+NO5	0.00	0.00	~~1476.73~~	~~1634.96~~	~~3.00~~	0.00
6100	NO4	NO2+NO5	0.00	0.00	~~1476.73~~	~~1634.96~~	~~3.00~~	0.00
5300	NO5	NO2+NO5	0.00	0.00	~~1417.40~~	~~1574.89~~	~~3.50~~	0.00

5300	NO5	NO2+NO5	0.00	0.00	~~1417.40~~	~~1574.89~~	~~3.50~~	0.00
6500	NO7	NO3	749.00	0.85	881.18	979.08	3.56	3483.58
6500	NO7	NO3	0.00	0.00	~~1000.00~~	~~1100.00~~	~~3.56~~	0.00
6500	NO7	NO3	0.00	0.00	~~1000.00~~	~~1100.00~~	~~3.56~~	0.00
6500	NO7	NO3	0.00	0.00	~~1000.00~~	~~1100.00~~	~~3.56~~	0.00
6700	NO8	NO4	978.00	0.85	1150.59	1278.43	3.59	4592.13
6700	NO8	NO4	0.00	0.00	~~1930.00~~	~~2144.44~~	3.59	0.00
3115	SE1	SE1	711.00	0.87	817.24	908.05	4.74	4305.05
3115	SE1	SE1	0.00	0.00	~~1388.15~~	~~1526.96~~	~~4.74~~	0.00
3115	SE1	SE1	0.00	0.00	~~1388.15~~	~~1526.96~~	~~4.74~~	0.00
3249	SE1	SE2	1100.00	0.89	1230.00	1357.00	4.54	6164.85
3249	SE1	SE2	0.00	0.00	~~1230.00~~	~~1357.00~~	~~4.54~~	0.00
3249	SE1	SE2	0.00	0.00	~~1230.00~~	~~1357.00~~	~~4.54~~	0.00
3249	SE1	SE2	0.00	0.00	~~1230.00~~	~~1357.00~~	~~4.54~~	0.00
3249	SE1	SE2	0.00	0.00	~~1230.00~~	~~1357.00~~	~~4.54~~	0.00
3249	SE1	SE2	0.00	0.00	~~1230.00~~	~~1357.00~~	~~4.54~~	0.00
3249	SE1	SE2	0.00	0.00	~~1230.00~~	~~1357.00~~	~~4.54~~	0.00
3245	SE2	SE2	739.00	0.88	839.77	933.08	3.30	3079.17
3000	SE3	SE3	950.00	0.81	1167.00	1300.00	5.97	7761.00
3000	SE3	SE3	950.00	0.81	1167.00	1300.00	5.97	7761.00
3000	SE3	SE3	0.00	0.00	~~1167.00~~	~~1300.00~~	~~5.97~~	0.00
30002	SE3	SE3	818.00	1.00	820.00	984.00	0.00	0.00
3300	SE3	SE3	800.00	0.80	1000.00	1100.00	6.00	6600.00
3300	SE3	SE3	800.00	0.80	1000.00	1100.00	6.00	6600.00
3300	SE3	SE3	800.00	0.80	1000.00	1100.00	6.00	6600.00
3359	SE3	SE3	1110.00	0.91	1217.00	1350.00	4.82	6507.00
3359	SE3	SE3	1000.00	0.82	1217.00	1350.00	4.82	6507.00
3359	SE3	SE3	1000.00	0.82	1217.00	1350.00	4.82	6507.00
3359	SE3	SE3	0.00	0.00	~~1217.00~~	~~1350.00~~	~~4.82~~	0.00
3359	SE3	SE3	0.00	0.00	~~1217.00~~	~~1350.00~~	~~4.82~~	0.00
3359	SE3	SE3	0.00	0.00	~~1217.00~~	~~1350.00~~	~~4.82~~	0.00
8500	SE4	SE4	703.00	0.85	827.06	918.95	7.00	6432.68
8500	SE4	SE4	0.00	0.00	~~1183.00~~	~~1300.00~~	~~7.00~~	0.00
8500	SE4	SE4	0.00	0.00	~~1183.00~~	~~1300.00~~	~~7.00~~	0.00
8500	SE4	SE4	0.00	0.00	~~1183.00~~	~~1300.00~~	~~7.00~~	0.00
8500	SE4	SE4	0.00	0.00	~~1183.00~~	~~1300.00~~	~~7.00~~	0.00
8500	SE4	SE4	0.00	0.00	~~1183.00~~	~~1300.00~~	~~7.00~~	0.00
			22568		**75006.22**			**135128.67**

Table A- 3: Scenario 2 - Production data.

Bus Number	Nordic44 Area Name	Elspot	P_{load} (MW)	Q_{load} (Mvar)
7100	FI1	FI1	677.44	200.00
7100	FI1	FI1	677.44	200.00
7000	FI2	FI2	754.02	70.00
7000	FI2	FI2	754.02	70.00
7000	FI2	FI2	754.02	70.00

7000	FI2	FI2	754.02	70.00
7000	FI2	FI2	754.02	70.00
7010	FI2	FI2	-506.00	600.00
7020	FI2	FI2	198.00	-4.00
5500	NO1	NO1	844.75	200.00
5500	NO1	NO1	844.75	200.00
5100	NO6	NO1	442.49	70.00
5400	NO2	NO2	611.38	100.00
5600	NO3	NO2	358.85	125.00
5600	NO3	NO2	358.85	125.00
5610	NO3	NO2	-822.00	363.00
5620	NO3	NO2	-518.00	175.00
6100	NO4	NO2	637.96	400.00
6100	NO4	NO2	637.96	400.00
6500	NO7	NO3	630.00	333.00
6500	NO7	NO3	630.00	333.00
6500	NO7	NO3	630.00	333.00
6700	NO8	NO4	1280.00	150.00
5300	NO5	NO5	1253.00	-70.00
3115	SE1	SE1	393.00	650.00
3100	SE2	SE1	393.00	110.00
3249	SE1	SE2	1368.00	650.00
3000	SE3	SE3	629.44	567.00
3000	SE3	SE3	629.44	567.00
3000	SE3	SE3	629.44	567.00
3020	SE3	SE3	506.00	616.00
3300	SE3	SE3	539.37	400.00
3300	SE3	SE3	539.37	400.00
3359	SE3	SE3	647.24	600.00
3359	SE3	SE3	647.24	600.00
3359	SE3	SE3	647.24	600.00
3359	SE3	SE3	647.24	600.00
3360	SE3	SE3	-2.00	262.00
8500	SE4	SE4	491.67	433.00
8500	SE4	SE4	491.67	433.00
8500	SE4	SE4	491.67	433.00
8600	SE4	SE4	95.00	10.00
8700	SE4	SE4	-1.00	0.00

Table A- 4: Scenario 2 - Load data.

APPENDIX B - LOAD FLOW DATA

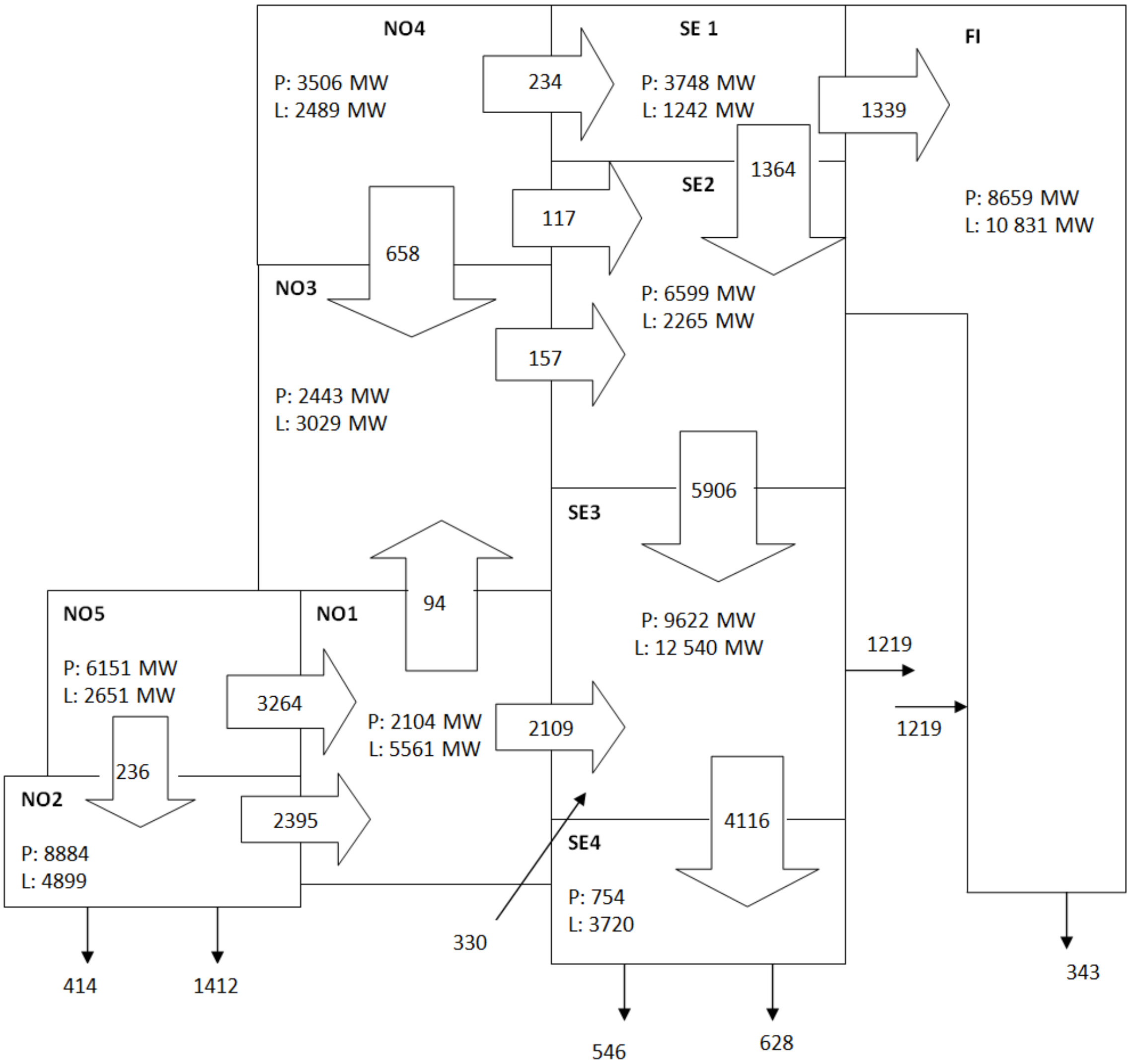

Figure B- 1: Scenario 1 - Load flow with real values from Nord Pool Spot [61].

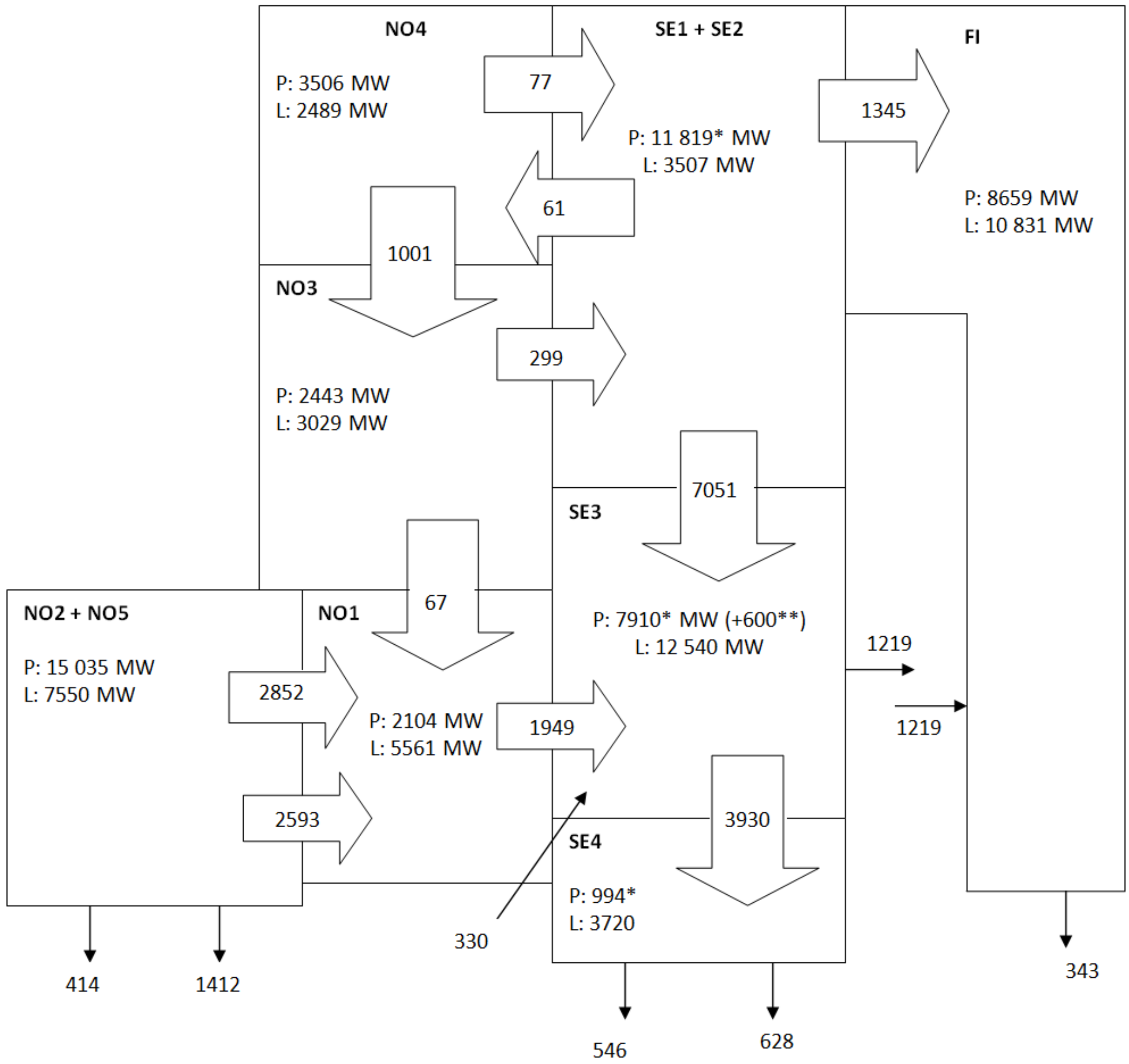

Figure B- 2: Scenario 1 - Load flow simulated in Nordic44 (* means the original value has been modified due to conflicts when modeling, means deviation on swing bus).**

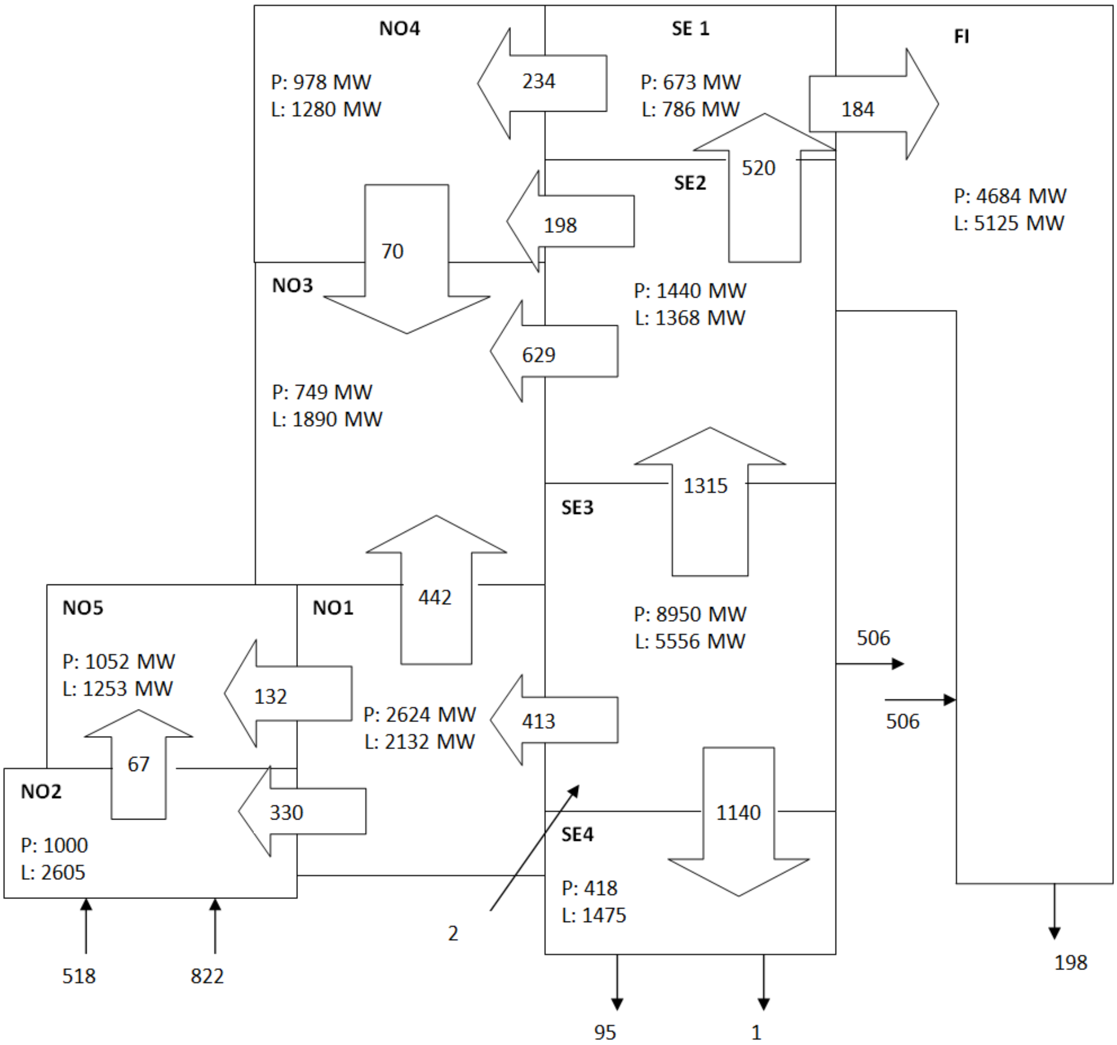

Figure B- 3: Scenario 2 - Load flow with real values from Nord Pool Spot [61].

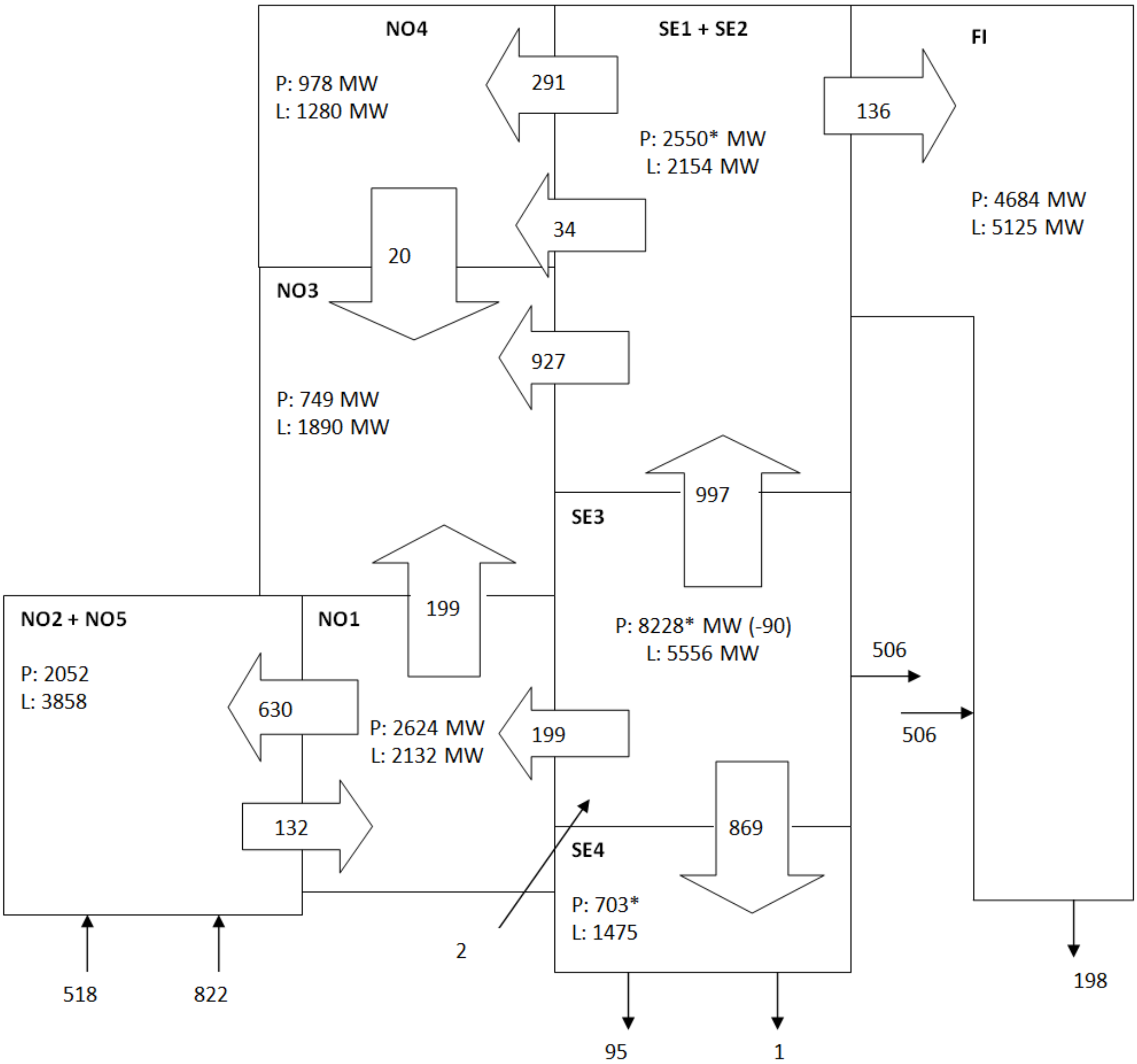

Figure B- 4: Scenario 2 - Load flow simulated in Nordic44 (* means the original value has been modified due to conflicts when modeling, ** means deviation on swing bus).

APPENDIX C - DYNAMIC MODELS IN NORDIC44

Bus Number	Generator	Exciter	Turbine Governor	If Hygov; A_t	Stabilizer
7100	GENSAL	SCRX	HYGOV	1.01	STAB1
7100	GENSAL	SCRX	HYGOV	1.01	STAB1
7100	GENSAL	SCRX	HYGOV	1.01	STAB1
7000	GENROU	IEEET2	IEESGO		STAB1
7000	GENROU	IEEET2	IEESGO		STAB1
7000	GENROU	IEEET2	IEESGO		STAB1
7000	GENROU	IEEET2	IEESGO		STAB1
7000	GENROU	IEEET2	IEESGO		STAB1
7000	GENROU	IEEET2	IEESGO		STAB1
7000	GENROU	IEEET2	IEESGO		STAB1
7000	GENROU	IEEET2	IEESGO		STAB1
7000	GENROU	IEEET2	IEESGO		STAB1
5500	GENSAL	SEXS	HYGOV	1.10	None
5100	GENSAL	SEXS	HYGOV	1.10	None
5400	GENSAL	SEXS	HYGOV	1.10	None
5400	GENSAL	SEXS	HYGOV	1.10	None
5600	GENSAL	SCRX	HYGOV	1.10	None
5600	GENSAL	SCRX	HYGOV	1.10	None
6000	GENSAL	SEXS	HYGOV	1.10	None
6100	GENSAL	SCRX	HYGOV	1.10	STAB1
6100	GENSAL	SCRX	HYGOV	1.10	STAB1
6100	GENSAL	SCRX	HYGOV	1.10	STAB1
6100	GENSAL	SCRX	HYGOV	1.10	STAB1
6100	GENSAL	SCRX	HYGOV	1.10	STAB1
5300	GENSAL	SCRX	HYGOV	1.10	STAB1
5300	GENSAL	SCRX	HYGOV	1.10	STAB1
6500	GENSAL	SEXS	HYGOV	1.10	None
6500	GENSAL	SEXS	HYGOV	1.10	None
6500	GENSAL	SEXS	HYGOV	1.10	None
6500	GENSAL	SEXS	HYGOV	1.10	None
6700	GENSAL	SCRX	HYGOV	1.10	STAB1
6700	GENSAL	SCRX	HYGOV	1.10	STAB1
3115	GENSAL	SCRX	HYGOV	1.06	STAB1
3115	GENSAL	SCRX	HYGOV	1.06	STAB1
3115	GENSAL	SCRX	HYGOV	1.06	STAB1
3249	GENSAL	SCRX	HYGOV	1.01	None
3249	GENSAL	SCRX	HYGOV	1.10	None
3249	GENSAL	SCRX	HYGOV	1.10	None
3249	GENSAL	SCRX	HYGOV	1.10	None
3249	GENSAL	SCRX	HYGOV	1.10	None
3249	GENSAL	SCRX	HYGOV	1.10	None
3249	GENSAL	SCRX	HYGOV	1.10	None
3245	GENSAL	SCRX	HYGOV	1.10	None
3000	GENROU	IEEET2	IEESGO		STAB1

3000	GENROU	IEEET2	IEESGO		STAB1
3000	GENROU	IEEET2	IEESGO		STAB1
3300	GENROU	SCRX	IEESGO		STAB1
3300	GENROU	SCRX	IEESGO		STAB1
3300	GENROU	SCRX	IEESGO		STAB1
3359	GENROU	SCRX	IEESGO		STAB1
3359	GENROU	SCRX	IEESGO		STAB1
3359	GENROU	SCRX	IEESGO		STAB1
3359	GENROU	SCRX	IEESGO		STAB1
3359	GENROU	SCRX	IEESGO		STAB1
3359	GENROU	SCRX	IEESGO		STAB1
8500	GENROU	SCRX	IEESGO		STAB1
8500	GENROU	SCRX	IEESGO		STAB1
8500	GENROU	SCRX	IEESGO		STAB1
8500	GENROU	SCRX	IEESGO		STAB1
8500	GENROU	SCRX	IEESGO		STAB1
8500	GENROU	SCRX	IEESGO		STAB1

Table C- 1: Dynamic models at the different buses.

APPENDIX D - DYNAMIC FILE SCENARIO 1

```
3000 'GENROU' 1     5.0000      0.50000E-01   1.0000       0.50000E-01
      5.9700        0.0000       2.2200       2.1300       0.36000
     0.46800       0.22500      0.16875      0.10890       0.37795    /
3000 'STAB1' 1     10.000       3.0000       2.5000        0.20000
     1.0000        1.0000      0.1000 /
3000 'IEEET2' 1     0.0000       729.00      0.40000E-01   5.3200
     -4.0500        1.0000      0.44000      0.66700E-01   2.0000
     0.44000        6.5000      0.54000E-01   8.0000       0.20200    /
3000 'IEESGO' 1    0.10000E-01   0.0000      0.15000       0.30000
      8.0000       0.40000       0.0000      0.70000       0.43000
      1.0000        0.0000     /
3000 'GENROU' 2     5.0000      0.50000E-01   1.0000       0.50000E-01
      5.9700        0.0000       2.2200       2.1300       0.36000
     0.46800       0.22500      0.16875      0.10890       0.37795    /
3000 'STAB1' 2     10.000       3.0000       2.5000        0.20000
     1.0000        1.0000      0.1000 /
3000 'IEEET2' 2     0.0000       729.00      0.40000E-01   5.3200
     -4.0500        1.0000      0.44000      0.66700E-01   2.0000
     0.44000        6.5000      0.54000E-01   8.0000       0.20200    /
3000 'IEESGO' 2    0.10000E-01   0.0000      0.15000       0.30000
      8.0000       0.40000       0.0000      0.70000       0.43000
      1.0000        0.0000     /
3000 'GENROU' 3     5.0000      0.50000E-01   1.0000       0.50000E-01
      5.9700        0.0000       2.2200       2.1300       0.36000
     0.46800       0.22500      0.16875      0.10890       0.37795    /
3000 'STAB1' 3     10.000       3.0000       2.5000        0.20000
     1.0000        1.0000      0.1000 /
3000 'IEEET2' 3     0.0000       729.00      0.40000E-01   5.3200
     -4.0500        1.0000      0.44000      0.66700E-01   2.0000
     0.44000        6.5000      0.54000E-01   8.0000       0.20200    /
3000 'IEESGO' 3    0.10000E-01   0.0000      0.15000       0.30000
      8.0000       0.40000       0.0000      0.70000       0.43000
      1.0000        0.0000     /
3100 'GENSAL' 1     4.0000      0.60000E-01  0.10000        5.0400
      0.0000       0.65000      0.39000      0.19000       0.11692
      0.87690E-01  0.10239      0.27420    /
3100 'SCRX'   1    0.25385       13.000       31.000       0.50000E-01
      0.0000        4.0000       0.0000       0.0000     /
3100 'HYGOV'  1    1.05000E-01  1.60000       1.3000       0.50000E-01
     0.60000       0.10000       1.0000       0.0000        2.0000
      1.0022       0.00000      0.10000    /
3115 'GENSAL' 1     7.5700      0.45000E-01  0.10000        4.7410
      0.0000       0.94600      0.56500      0.29000       0.23000
     0.11077       0.10239      0.27420    /
3115 'STAB1' 1     10.000       3.0000       2.5000        0.20000
     1.0000        1.0000      0.1000 /
3115 'SCRX'   1    0.25385       13.000       31.000       0.50000E-01
      0.0000        4.0000       0.0000       0.0000     /
3115 'HYGOV'  1    1.05000E-01  1.60000       1.3000       0.50000E-01
     0.60000       0.10000       1.0000       0.0000        2.0000
      1.0577       0.00000      0.10000    /
3115 'GENSAL' 2     7.5700      0.45000E-01  0.10000        4.7410
      0.0000       0.94600      0.56500      0.29000       0.23000
     0.11077       0.10239      0.27420    /
3115 'STAB1' 2     10.000       3.0000       2.5000        0.20000
     1.0000        1.0000      0.1000 /
3115 'SCRX'   2    0.25385       13.000       31.000       0.50000E-01
      0.0000        4.0000       0.0000       0.0000     /
3115 'HYGOV'  2    1.05000E-01  1.60000       1.3000       0.50000E-01
     0.60000       0.10000       1.0000       0.0000        2.0000
      1.0577       0.00000      0.10000    /
3115 'GENSAL' 3     7.5700      0.45000E-01  0.10000        4.7410
      0.0000       0.94600      0.56500      0.29000       0.23000
     0.11077       0.10239      0.27420    /
3115 'STAB1' 3     10.000       3.0000       2.5000        0.20000
     1.0000        1.0000      0.1000 /
3115 'SCRX'   3    0.25385       13.000       31.000       0.50000E-01
      0.0000        4.0000       0.0000       0.0000     /
3115 'HYGOV'  3    1.05000E-01  1.60000       1.3000       0.50000E-01
     0.60000       0.10000       1.0000       0.0000        2.0000
      1.0577       0.00000      0.10000    /
3245 'GENSAL' 1     5.0000      0.60000E-01  0.10000        3.3000
      0.0000       0.75000      0.50000      0.25000       0.15385
     0.11538       0.10239      0.27420    /
3245 'SCRX'   1    0.25385       13.000       31.000       0.50000E-01
      0.0000        4.0000       0.0000       0.0000     /
3245 'HYGOV'  1    1.05000E-01  1.60000       1.3000       0.50000E-01
     0.60000       0.10000       1.0000       0.0000        2.0000
      1.0100       0.00000      0.10000    /
3249 'GENSAL' 1     10.130      0.60000E-01  0.10000        4.5430
      0.0000        1.0360      0.63000      0.28000       0.21000
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       0.11538      0.10239      0.27420    /
  3249 'SCRX'   1    0.25385      13.000       31.000       0.50000E-01
        0.0000       4.0000       0.0000       0.0000    /
  3249 'HYGOV'  1   1.05000E-01  1.60000       1.3000       0.50000E-01
       0.60000      0.10000       1.0000       0.0000       2.0000
        1.1000      0.00000      0.10000    /
  3249 'GENSAL' 2     10.130     0.60000E-01  0.10000       4.5430
        0.0000       1.0360      0.63000      0.28000      0.21000
       0.11538      0.10239      0.27420    /
  3249 'SCRX'   2    0.25385      13.000       31.000       0.50000E-01
        0.0000       4.0000       0.0000       0.0000    /
  3249 'HYGOV'  2   1.05000E-01  1.60000       1.3000       0.50000E-01
       0.60000      0.10000       1.0000       0.0000       2.0000
        1.1000      0.00000      0.10000    /
  3249 'GENSAL' 3     10.130     0.60000E-01  0.10000       4.5430
        0.0000       1.0360      0.63000      0.28000      0.21000
       0.11538      0.10239      0.27420    /
  3249 'SCRX'   3    0.25385      13.000       31.000       0.50000E-01
        0.0000       4.0000       0.0000       0.0000    /
  3249 'HYGOV'  3   1.05000E-01  1.60000       1.3000       0.50000E-01
       0.60000      0.10000       1.0000       0.0000       2.0000
        1.1000      0.00000      0.10000    /
  3249 'GENSAL' 4     10.130     0.60000E-01  0.10000       4.5430
        0.0000       1.0360      0.63000      0.28000      0.21000
       0.11538      0.10239      0.27420    /
  3249 'SCRX'   4    0.25385      13.000       31.000       0.50000E-01
        0.0000       4.0000       0.0000       0.0000    /
  3249 'HYGOV'  4   1.05000E-01  1.60000       1.3000       0.50000E-01
       0.60000      0.10000       1.0000       0.0000       2.0000
        1.1000      0.00000      0.10000    /
  3249 'GENSAL' 5     10.130     0.60000E-01  0.10000       4.5430
        0.0000       1.0360      0.63000      0.28000      0.21000
       0.11538      0.10239      0.27420    /
  3249 'SCRX'   5    0.25385      13.000       31.000       0.50000E-01
        0.0000       4.0000       0.0000       0.0000    /
  3249 'HYGOV'  5   1.05000E-01  1.60000       1.3000       0.50000E-01
       0.60000      0.10000       1.0000       0.0000       2.0000
        1.1000      0.00000      0.10000    /
  3249 'GENSAL' 6     10.130     0.60000E-01  0.10000       4.5430
        0.0000       1.0360      0.63000      0.28000      0.21000
       0.11538      0.10239      0.27420    /
  3249 'SCRX'   6    0.25385      13.000       31.000       0.50000E-01
        0.0000       4.0000       0.0000       0.0000    /
  3249 'HYGOV'  6   1.05000E-01  1.60000       1.3000       0.50000E-01
       0.60000      0.10000       1.0000       0.0000       2.0000
        1.1000      0.00000      0.10000    /
  3249 'GENSAL' 7     10.130     0.60000E-01  0.10000       4.5430
        0.0000       1.0360      0.63000      0.28000      0.21000
       0.11538      0.10239      0.27420    /
  3249 'SCRX'   7    0.25385      13.000       31.000       0.50000E-01
        0.0000       4.0000       0.0000       0.0000    /
  3249 'HYGOV'  7   1.05000E-01  1.60000       1.3000       0.50000E-01
       0.60000      0.10000       1.0000       0.0000       2.0000
        1.1000      0.00000      0.10000    /
  3300 'GENROU' 1     10.800     0.50000E-01   1.0000       0.50000E-01
        6.0000       0.0000       2.4200       2.0000      0.23000
       0.41080      0.16000      0.14812      0.10890      0.37795    /
  3300 'STAB1' 1    10.000       3.0000       2.5000      0.20000
       1.0000       1.0000      0.1000 /
  3300 'SCRX'   1     0.0000     0.40000E-01   10.000       0.40000E-01
        0.0000       5.0000       0.0000       0.0000    /
  3300 'IEESGO' 1   0.10000E-01   0.0000      0.15000      0.30000
        8.0000      0.40000       0.0000      0.70000      0.43000
        1.0000       0.0000    /
  3300 'GENROU' 2     10.800     0.50000E-01   1.0000       0.50000E-01
        6.0000       0.0000       2.4200       2.0000      0.23000
       0.41080      0.16000      0.14812      0.10890      0.37795    /
  3300 'STAB1' 2    10.000       3.0000       2.5000      0.20000
       1.0000       1.0000      0.1000 /
  3300 'SCRX'   2     0.0000     0.40000E-01   10.000       0.40000E-01
        0.0000       5.0000       0.0000       0.0000    /
  3300 'IEESGO' 2   0.10000E-01   0.0000      0.15000      0.30000
        8.0000      0.40000       0.0000      0.70000      0.43000
        1.0000       0.0000    /
  3300 'GENROU' 3     10.800     0.50000E-01   1.0000       0.50000E-01
        6.0000       0.0000       2.4200       2.0000      0.23000
       0.41080      0.16000      0.14812      0.10890      0.37795    /
  3300 'STAB1' 3    10.000       3.0000       2.5000      0.20000
       1.0000       1.0000      0.1000 /
  3300 'SCRX'   3     0.0000     0.40000E-01   10.000       0.40000E-01
        0.0000       5.0000       0.0000       0.0000    /
  3300 'IEESGO' 3   0.10000E-01   0.0000      0.15000      0.30000
        8.0000      0.40000       0.0000      0.70000      0.43000
        1.0000       0.0000    /
  3359 'GENROU' 1     4.7500     0.50000E-01   1.0000       0.50000E-01
        4.8200       0.0000       2.1300       2.0300      0.31000
       0.40300      0.19370      0.14531      0.10890      0.37795    /
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3359 'STAB1' 1      10.000       3.0000       2.5000       0.20000
     1.0000         1.0000      0.1000 /
3359 'SCRX'   1     0.20000      10.000        165.00       0.40000E-01
      0.0000         5.0000       0.0000        0.0000     /
3359 'IEESGO' 1     0.10000E-01   0.0000       0.15000      0.30000
      8.0000        0.40000       0.0000       0.70000      0.43000
      1.0000         0.0000     /
3359 'GENROU' 2      4.7500      0.50000E-01   1.0000      0.50000E-01
      4.8200         0.0000       2.1300        2.0300      0.31000
     0.40300        0.19370      0.14531       0.10890      0.37795     /
3359 'STAB1' 2      10.000       3.0000       2.5000       0.20000
     1.0000         1.0000      0.1000 /
3359 'SCRX'   2     0.20000      10.000        165.00       0.40000E-01
      0.0000         5.0000       0.0000        0.0000     /
3359 'IEESGO' 2     0.10000E-01   0.0000       0.15000      0.30000
      8.0000        0.40000       0.0000       0.70000      0.43000
      1.0000         0.0000     /
3359 'GENROU' 3      4.7500      0.50000E-01   1.0000      0.50000E-01
      4.8200         0.0000       2.1300        2.0300      0.31000
     0.40300        0.19370      0.14531       0.10890      0.37795     /
3359 'STAB1' 3      10.000       3.0000       2.5000       0.20000
     1.0000         1.0000      0.1000 /
3359 'SCRX'   3     0.20000      10.000        165.00       0.40000E-01
      0.0000         5.0000       0.0000        0.0000     /
3359 'IEESGO' 3     0.10000E-01   0.0000       0.15000      0.30000
      8.0000        0.40000       0.0000       0.70000      0.43000
      1.0000         0.0000     /
3359 'GENROU' 4      4.7500      0.50000E-01   1.0000      0.50000E-01
      4.8200         0.0000       2.1300        2.0300      0.31000
     0.40300        0.19370      0.14531       0.10890      0.37795     /
3359 'STAB1' 4      10.000       3.0000       2.5000       0.20000
     1.0000         1.0000      0.1000 /
3359 'SCRX'   4     0.20000      10.000        165.00       0.40000E-01
      0.0000         5.0000       0.0000        0.0000     /
3359 'IEESGO' 4     0.10000E-01   0.0000       0.15000      0.30000
      8.0000        0.40000       0.0000       0.70000      0.43000
      1.0000         0.0000     /
3359 'GENROU' 5      4.7500      0.50000E-01   1.0000      0.50000E-01
      4.8200         0.0000       2.1300        2.0300      0.31000
     0.40300        0.19370      0.14531       0.10890      0.37795     /
3359 'STAB1' 5      10.000       3.0000       2.5000       0.20000
     1.0000         1.0000      0.1000 /
3359 'SCRX'   5     0.20000      10.000        165.00       0.40000E-01
      0.0000         5.0000       0.0000        0.0000     /
3359 'IEESGO' 5     0.10000E-01   0.0000       0.15000      0.30000
      8.0000        0.40000       0.0000       0.70000      0.43000
      1.0000         0.0000     /
3359 'GENROU' 6      4.7500      0.50000E-01   1.0000      0.50000E-01
      4.8200         0.0000       2.1300        2.0300      0.31000
     0.40300        0.19370      0.14531       0.10890      0.37795     /
3359 'STAB1' 6      10.000       3.0000       2.5000       0.20000
     1.0000         1.0000      0.1000 /
3359 'SCRX'   6     0.20000      10.000        165.00       0.40000E-01
      0.0000         5.0000       0.0000        0.0000     /
3359 'IEESGO' 6     0.10000E-01   0.0000       0.15000      0.30000
      8.0000        0.40000       0.0000       0.70000      0.43000
      1.0000         0.0000     /
5100 'GENSAL' 1      4.9629      0.50000E-01  0.15000       3.9871
      0.0000         1.1332      0.68315      0.24302      0.15135
     0.13405        0.10000      0.30000     /
5100 'SEXS'   1     0.50000E-01   100.00        200.00      0.50000
      0.0000         4.0000     /
5100 'HYGOV'  1     1.45000E-01  1.60000        1.3000      0.50000E-01
     0.60000        0.20000       1.0000        0.0000       2.0000
      1.1000        0.00000      0.10000     /
5300 'GENSAL' 1      6.4000      0.50000E-01  0.15000       3.5000
      0.0000         1.1400      0.84000      0.34000      0.26000
     0.20000        0.10000      0.30000     /
5300 'STAB1' 1      10.000       3.0000       2.5000       0.20000
     1.0000         1.0000      0.1000 /
5300 'SCRX'   1     0.25385      13.000        61.000       0.50000E-01
      0.0000         4.0000       0.0000        0.0000     /
5300 'HYGOV'  1     1.45000E-01  1.60000        1.3000      0.50000E-01
     0.60000        0.20000       1.0000        0.0000       2.0000
      1.1000        0.00000      0.10000     /
5300 'GENSAL' 2      6.4000      0.50000E-01  0.15000       3.5000
      0.0000         1.1400      0.84000      0.34000      0.26000
     0.20000        0.10000      0.30000     /
5300 'STAB1' 2      10.000       3.0000       2.5000       0.20000
     1.0000         1.0000      0.1000 /
5300 'SCRX'   2     0.25385      13.000        61.000       0.50000E-01
      0.0000         4.0000       0.0000        0.0000     /
5300 'HYGOV'  2     1.45000E-01  1.60000        1.3000      0.50000E-01
     0.60000        0.20000       1.0000        0.0000       2.0000
      1.1000        0.00000      0.10000     /
5400 'GENSAL' 1      6.5000      0.50000E-01  0.15000       4.1000
      0.0000         1.0200      0.63000      0.25000      0.16000
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   0.13000      0.10000      0.30000     /
5400 'SEXS'   1   0.50000E-01   100.00       200.00       0.50000
    0.0000      4.0000     /
5400 'HYGOV'  1   1.45000E-01  1.60000       1.3000       0.50000E-01
   0.60000      0.20000      1.0000       0.0000        2.0000
    1.1000      0.00000      0.10000     /
5400 'GENSAL' 2    6.5000      0.50000E-01  0.15000       4.1000
    0.0000      1.0200       0.63000      0.25000      0.16000
   0.13000      0.10000      0.30000     /
5400 'SEXS'   2   0.50000E-01   100.00       200.00       0.50000
    0.0000      4.0000     /
5400 'HYGOV'  2   1.45000E-01  1.60000       1.3000       0.50000E-01
   0.60000      0.20000      1.0000       0.0000        2.0000
    1.1000      0.00000      0.10000     /
5500 'GENSAL' 1    7.1980      0.50000E-01  0.15000       3.0000
    0.0000      1.2364       0.65567      0.37415      0.22825
   0.16194      0.10000      0.30000     /
5500 'SEXS'   1   0.50000E-01   100.00       200.00       0.50000
    0.0000      4.0000     /
5500 'HYGOV'  1   1.45000E-01  1.60000       1.3000       0.50000E-01
   0.60000      0.20000      1.0000       0.0000        2.0000
    1.1000      0.00000      0.10000     /
5600 'GENSAL' 1    7.8500      0.50000E-01  0.15000       3.5000
    0.0000      1.0000       0.51325      0.38000      0.28000
   0.21000      0.10000      0.30000     /
5600 'SCRX'   1   0.25385       13.000       61.000       0.50000E-01
    0.0000      4.0000       0.0000       0.0000     /
5600 'HYGOV'  1   1.45000E-01  1.60000       1.3000       0.50000E-01
   0.60000      0.20000      1.0000       0.0000        2.0000
    1.1000      0.00000      0.10000     /
5600 'GENSAL' 2    7.8500      0.50000E-01  0.15000       3.5000
    0.0000      1.0000       0.51325      0.38000      0.28000
   0.21000      0.10000      0.30000     /
5600 'SCRX'   2   0.25385       13.000       61.000       0.50000E-01
    0.0000      4.0000       0.0000       0.0000     /
5600 'HYGOV'  2   1.45000E-01  1.60000       1.3000       0.50000E-01
   0.60000      0.20000      1.0000       0.0000        2.0000
    1.1000      0.00000      0.10000     /
6000 'GENSAL' 1    9.7000      0.50000E-01  0.15000       3.5000
    0.0000      1.2800       0.94000      0.37000      0.28000
   0.20000      0.10000      0.30000     /
6000 'SEXS'   1    1.0000      0.10000       20.000       0.10000
   -4.0000      4.0000     /
6000 'HYGOV'  1   1.45000E-01  1.60000       1.3000       0.50000E-01
   0.60000      0.20000      1.0000       0.0000        2.0000
    1.1000      0.00000      0.10000     /
6100 'GENSAL' 1    9.9000      0.50000E-01  0.15000       3.0000
    0.0000      1.2000       0.73000      0.37000      0.18000
   0.15000      0.10000      0.30000     /
6100 'STAB1' 1    10.000       3.0000       2.5000       0.20000
   1.0000       1.0000      0.1000 /
6100 'SCRX'   1   0.25385       13.000       61.000       0.50000E-01
    0.0000      4.0000       0.0000       0.0000     /
6100 'HYGOV'  1   1.45000E-01  1.60000       1.3000       0.50000E-01
   0.60000      0.20000      1.0000       0.0000        2.0000
    1.1000      0.00000      0.10000     /
6100 'GENSAL' 2    9.9000      0.50000E-01  0.15000       3.0000
    0.0000      1.2000       0.73000      0.37000      0.18000
   0.15000      0.10000      0.30000     /
6100 'STAB1' 2    10.000       3.0000       2.5000       0.20000
   1.0000       1.0000      0.1000 /
6100 'SCRX'   2   0.25385       13.000       61.000       0.50000E-01
    0.0000      4.0000       0.0000       0.0000     /
6100 'HYGOV'  2   1.45000E-01  1.60000       1.3000       0.50000E-01
   0.60000      0.20000      1.0000       0.0000        2.0000
    1.1000      0.00000      0.10000     /
6100 'GENSAL' 3    9.9000      0.50000E-01  0.15000       3.0000
    0.0000      1.2000       0.73000      0.37000      0.18000
   0.15000      0.10000      0.30000     /
6100 'STAB1' 3    10.000       3.0000       2.5000       0.20000
   1.0000       1.0000      0.1000 /
6100 'SCRX'   3   0.25385       13.000       61.000       0.50000E-01
    0.0000      4.0000       0.0000       0.0000     /
6100 'HYGOV'  3   1.45000E-01  1.60000       1.3000       0.50000E-01
   0.60000      0.20000      1.0000       0.0000        2.0000
    1.1000      0.00000      0.10000     /
6100 'GENSAL' 4    9.9000      0.50000E-01  0.15000       3.0000
    0.0000      1.2000       0.73000      0.37000      0.18000
   0.15000      0.10000      0.30000     /
6100 'STAB1' 4    10.000       3.0000       2.5000       0.20000
   1.0000       1.0000      0.1000 /
6100 'SCRX'   4   0.25385       13.000       61.000       0.50000E-01
    0.0000      4.0000       0.0000       0.0000     /
6100 'HYGOV'  4   1.45000E-01  1.60000       1.3000       0.50000E-01
   0.60000      0.20000      1.0000       0.0000        2.0000
    1.1000      0.00000      0.10000     /
6100 'GENSAL' 5    9.9000      0.50000E-01  0.15000       3.0000
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      0.0000       1.2000      0.73000      0.37000      0.18000
     0.15000      0.10000      0.30000     /
6100 'STAB1' 5    10.000      3.0000       2.5000       0.20000
     1.0000       1.0000      0.1000 /
6100 'SCRX'   5   0.25385      13.000       61.000      0.50000E-01
      0.0000       4.0000      0.0000       0.0000     /
6100 'HYGOV'  5   1.45000E-01  1.60000      1.3000      0.50000E-01
     0.60000      0.20000      1.0000       0.0000       2.0000
      1.1000      0.00000      0.10000     /
6500 'GENSAL' 1    5.4855      0.50000E-01  0.15000      3.5580
      0.0000       1.0679      0.64200      0.23865      0.15802
     0.13514      0.10000      0.30000     /
6500 'SEXS'   1   0.50000E-01   100.00       200.00      0.50000
      0.0000       4.0000     /
6500 'HYGOV'  1   1.45000E-01  1.60000      1.3000      0.50000E-01
     0.60000      0.20000      1.0000       0.0000       2.0000
      1.1000      0.00000      0.10000     /
6500 'GENSAL' 2    5.4855      0.50000E-01  0.15000      3.5580
      0.0000       1.0679      0.64200      0.23865      0.15802
     0.13514      0.10000      0.30000     /
6500 'SEXS'   2   0.50000E-01   100.00       200.00      0.50000
      0.0000       4.0000     /
6500 'HYGOV'  2   1.45000E-01  1.60000      1.3000      0.50000E-01
     0.60000      0.20000      1.0000       0.0000       2.0000
      1.1000      0.00000      0.10000     /
6500 'GENSAL' 3    5.4855      0.50000E-01  0.15000      3.5580
      0.0000       1.0679      0.64200      0.23865      0.15802
     0.13514      0.10000      0.30000     /
6500 'SEXS'   3   0.50000E-01   100.00       200.00      0.50000
      0.0000       4.0000     /
6500 'HYGOV'  3   1.45000E-01  1.60000      1.3000      0.50000E-01
     0.60000      0.20000      1.0000       0.0000       2.0000
      1.1000      0.00000      0.10000     /
6500 'GENSAL' 4    5.4855      0.50000E-01  0.15000      3.5580
      0.0000       1.0679      0.64200      0.23865      0.15802
     0.13514      0.10000      0.30000     /
6500 'SEXS'   4   0.50000E-01   100.00       200.00      0.50000
      0.0000       4.0000     /
6500 'HYGOV'  4   1.45000E-01  1.60000      1.3000      0.50000E-01
     0.60000      0.20000      1.0000       0.0000       2.0000
      1.1000      0.00000      0.10000     /
6700 'GENSAL' 1    5.2400      0.50000E-01  0.15000      3.5920
      0.0000       1.1044      0.66186      0.25484      0.17062
     0.14737      0.10000      0.30000     /
6700 'STAB1' 1    10.000      3.0000       2.5000       0.20000
     1.0000       1.0000      0.1000 /
6700 'SCRX'   1   0.25385      13.000       61.000      0.50000E-01
      0.0000       4.0000      0.0000       0.0000     /
6700 'HYGOV'  1   1.45000E-01  1.60000      1.3000      0.50000E-01
     0.60000      0.20000      1.0000       0.0000       2.0000
      1.1000      0.00000      0.10000     /
6700 'GENSAL' 2    5.2400      0.50000E-01  0.15000      3.5920
      0.0000       1.1044      0.66186      0.25484      0.17062
     0.14737      0.10000      0.30000     /
6700 'STAB1' 2    10.000      3.0000       2.5000       0.20000
     1.0000       1.0000      0.1000 /
6700 'SCRX'   2   0.25385      13.000       61.000      0.50000E-01
      0.0000       4.0000      0.0000       0.0000     /
6700 'HYGOV'  2   1.450000E-01  1.60000      1.3000      0.50000E-01
     0.60000      0.20000      1.0000       0.0000       2.0000
      1.1000      0.00000      0.10000     /
7000 'GENROU' 1    10.000      0.50000E-01   1.0000      0.50000E-01
      5.5000       0.0000      2.2200       2.1300      0.36000
     0.46800      0.22500      0.16875      0.10890      0.37795     /
7000 'STAB1' 1    10.000      3.0000       2.5000       0.20000
     1.0000       1.0000      0.1000 /
7000 'IEEET2' 1    0.0000      800.00      0.40000E-01   5.3200
     -4.0500       1.0000      0.44000      0.66700E-01   2.0000
     0.44000       6.5000      0.54000E-01   8.0000      0.20200     /
7000 'IEESGO' 1   0.10000E-01   0.0000      0.15000      0.30000
      8.0000      0.40000       0.0000      0.70000      0.43000
      1.0000       0.0000     /
7000 'GENROU' 2    10.000      0.50000E-01   1.0000      0.50000E-01
      5.5000       0.0000      2.2200       2.1300      0.36000
     0.46800      0.22500      0.16875      0.10890      0.37795     /
7000 'STAB1' 2    10.000      3.0000       2.5000       0.20000
     1.0000       1.0000      0.1000 /
7000 'IEEET2' 2    0.0000      800.00      0.40000E-01   5.3200
     -4.0500       1.0000      0.44000      0.66700E-01   2.0000
     0.44000       6.5000      0.54000E-01   8.0000      0.20200     /
7000 'IEESGO' 2   0.10000E-01   0.0000      0.15000      0.30000
      8.0000      0.40000       0.0000      0.70000      0.43000
      1.0000       0.0000     /
7000 'GENROU' 3    10.000      0.50000E-01   1.0000      0.50000E-01
      5.5000       0.0000      2.2200       2.1300      0.36000
     0.46800      0.22500      0.16875      0.10890      0.37795     /
7000 'STAB1' 3    10.000      3.0000       2.5000       0.20000
```

```
     1.0000       1.0000       0.1000 /
7000 'IEEET2' 3     0.0000       800.00       0.40000E-01   5.3200
     -4.0500       1.0000       0.44000       0.66700E-01   2.0000
     0.44000       6.5000       0.54000E-01   8.0000       0.20200     /
7000 'IEESGO' 3   0.10000E-01   0.0000       0.15000       0.30000
      8.0000       0.40000       0.0000       0.70000       0.43000
      1.0000       0.0000     /
7000 'GENROU' 4     10.000       0.50000E-01   1.0000       0.50000E-01
      5.5000       0.0000       2.2200       2.1300       0.36000
     0.46800       0.22500       0.16875       0.10890       0.37795     /
7000 'STAB1' 4     10.000       3.0000       2.5000       0.20000
     1.0000       1.0000       0.1000 /
7000 'IEEET2' 4     0.0000       800.00       0.40000E-01   5.3200
     -4.0500       1.0000       0.44000       0.66700E-01   2.0000
     0.44000       6.5000       0.54000E-01   8.0000       0.20200     /
7000 'IEESGO' 4   0.10000E-01   0.0000       0.15000       0.30000
      8.0000       0.40000       0.0000       0.70000       0.43000
      1.0000       0.0000     /
7000 'GENROU' 5     10.000       0.50000E-01   1.0000       0.50000E-01
      5.5000       0.0000       2.2200       2.1300       0.36000
     0.46800       0.22500       0.16875       0.10890       0.37795     /
7000 'STAB1' 5     10.000       3.0000       2.5000       0.20000
     1.0000       1.0000       0.1000 /
7000 'IEEET2' 5     0.0000       800.00       0.40000E-01   5.3200
     -4.0500       1.0000       0.44000       0.66700E-01   2.0000
     0.44000       6.5000       0.54000E-01   8.0000       0.20200     /
7000 'IEESGO' 5   0.10000E-01   0.0000       0.15000       0.30000
      8.0000       0.40000       0.0000       0.70000       0.43000
      1.0000       0.0000     /
7000 'GENROU' 6     10.000       0.50000E-01   1.0000       0.50000E-01
      5.5000       0.0000       2.2200       2.1300       0.36000
     0.46800       0.22500       0.16875       0.10890       0.37795     /
7000 'STAB1' 6     10.000       3.0000       2.5000       0.20000
     1.0000       1.0000       0.1000 /
7000 'IEEET2' 6     0.0000       800.00       0.40000E-01   5.3200
     -4.0500       1.0000       0.44000       0.66700E-01   2.0000
     0.44000       6.5000       0.54000E-01   8.0000       0.20200     /
7000 'IEESGO' 6   0.10000E-01   0.0000       0.15000       0.30000
      8.0000       0.40000       0.0000       0.70000       0.43000
      1.0000       0.0000     /
7000 'GENROU' 7     10.000       0.50000E-01   1.0000       0.50000E-01
      5.5000       0.0000       2.2200       2.1300       0.36000
     0.46800       0.22500       0.16875       0.10890       0.37795     /
7000 'STAB1' 7     10.000       3.0000       2.5000       0.20000
     1.0000       1.0000       0.1000 /
7000 'IEEET2' 7     0.0000       800.00       0.40000E-01   5.3200
     -4.0500       1.0000       0.44000       0.66700E-01   2.0000
     0.44000       6.5000       0.54000E-01   8.0000       0.20200     /
7000 'IEESGO' 7   0.10000E-01   0.0000       0.15000       0.30000
      8.0000       0.40000       0.0000       0.70000       0.43000
      1.0000       0.0000     /
7000 'GENROU' 8     10.000       0.50000E-01   1.0000       0.50000E-01
      5.5000       0.0000       2.2200       2.1300       0.36000
     0.46800       0.22500       0.16875       0.10890       0.37795     /
7000 'STAB1' 8     10.000       3.0000       2.5000       0.20000
     1.0000       1.0000       0.1000 /
7000 'IEEET2' 8     0.0000       800.00       0.40000E-01   5.3200
     -4.0500       1.0000       0.44000       0.66700E-01   2.0000
     0.44000       6.5000       0.54000E-01   8.0000       0.20200     /
7000 'IEESGO' 8   0.10000E-01   0.0000       0.15000       0.30000
      8.0000       0.40000       0.0000       0.70000       0.43000
      1.0000       0.0000     /
7000 'GENROU' 9     10.000       0.50000E-01   1.0000       0.50000E-01
      5.5000       0.0000       2.2200       2.1300       0.36000
     0.46800       0.22500       0.16875       0.10890       0.37795     /
7000 'STAB1' 9     10.000       3.0000       2.5000       0.20000
     1.0000       1.0000       0.1000 /
7000 'IEEET2' 9     0.0000       800.00       0.40000E-01   5.3200
     -4.0500       1.0000       0.44000       0.66700E-01   2.0000
     0.44000       6.5000       0.54000E-01   8.0000       0.20200     /
7000 'IEESGO' 9   0.10000E-01   0.0000       0.15000       0.30000
      8.0000       0.40000       0.0000       0.70000       0.43000
      1.0000       0.0000     /
7100 'GENSAL' 1     5.0000       0.60000E-01  0.10000       3.2000
      0.0000       0.75000       0.50000       0.25000       0.15385
     0.11538       0.10239       0.27420     /
7100 'STAB1' 1     10.000       3.0000       2.5000       0.20000
     1.0000       1.0000       0.1000 /
7100 'SCRX'   1    0.25385       13.000       61.000       0.50000E-01
      0.0000       4.0000       0.0000       0.0000     /
7100 'HYGOV'  1    1.05000E-01  1.60000      1.3000       0.50000E-01
     0.60000       0.10000       1.0000       0.0000       2.0000
      1.0100       0.00000       0.10000     /
7100 'GENSAL' 2     5.0000       0.60000E-01  0.10000       3.2000
      0.0000       0.75000       0.50000       0.25000       0.15385
     0.11538       0.10239       0.27420     /
7100 'STAB1' 2     10.000       3.0000       2.5000       0.20000
```

```
   1.0000        1.0000       0.1000 /
7100 'SCRX'   2   0.25385      13.000        61.000       0.50000E-01
    0.0000        4.0000       0.0000        0.0000     /
7100 'HYGOV'  2   1.05000E-01  1.60000       1.3000       0.50000E-01
   0.60000       0.10000       1.0000        0.0000        2.0000
    1.0100       0.00000      0.10000     /
7100 'GENSAL' 3    5.0000     0.60000E-01  0.10000        3.2000
    0.0000       0.75000      0.50000       0.25000       0.15385
   0.11538       0.10239      0.27420     /
7100 'STAB1' 3    10.000       3.0000       2.5000        0.20000
   1.0000        1.0000       0.1000 /
7100 'SCRX'   3   0.25385      13.000        61.000       0.50000E-01
    0.0000        4.0000       0.0000        0.0000     /
7100 'HYGOV'  3   1.05000E-01  1.60000       1.3000       0.50000E-01
   0.60000       0.10000       1.0000        0.0000        2.0000
    1.0100       0.00000      0.10000     /
8500 'GENROU' 1    10.000     0.50000E-01   1.0000        0.50000E-01
    7.0000        0.0000       2.4200        2.0000       0.23000
   0.41080       0.17062      0.14812       0.10890       0.37795     /
8500 'STAB1' 1    10.000       3.0000       2.5000        0.20000
   1.0000        1.0000       0.1000 /
8500 'SCRX'   1    0.0000     0.40000E-01   10.000        0.40000E-01
    0.0000        5.0000       0.0000        0.0000     /
8500 'IEESGO' 1   0.10000E-01   0.0000      0.15000       0.30000
    8.0000       0.40000       0.0000       0.70000       0.43000
    1.0000        0.0000     /
8500 'GENROU' 2    10.000     0.50000E-01   1.0000        0.50000E-01
    7.0000        0.0000       2.4200        2.0000       0.23000
   0.41080       0.17062      0.14812       0.10890       0.37795     /
8500 'STAB1' 2    10.000       3.0000       2.5000        0.20000
   1.0000        1.0000       0.1000 /
8500 'SCRX'   2    0.0000     0.40000E-01   10.000        0.40000E-01
    0.0000        5.0000       0.0000        0.0000     /
8500 'IEESGO' 2   0.10000E-01   0.0000      0.15000       0.30000
    8.0000       0.40000       0.0000       0.70000       0.43000
    1.0000        0.0000     /
8500 'GENROU' 3    10.000     0.50000E-01   1.0000        0.50000E-01
    7.0000        0.0000       2.4200        2.0000       0.23000
   0.41080       0.17062      0.14812       0.10890       0.37795     /
8500 'STAB1' 3    10.000       3.0000       2.5000        0.20000
   1.0000        1.0000       0.1000 /
8500 'SCRX'   3    0.0000     0.40000E-01   10.000        0.40000E-01
    0.0000        5.0000       0.0000        0.0000     /
8500 'IEESGO' 3   0.10000E-01   0.0000      0.15000       0.30000
    8.0000       0.40000       0.0000       0.70000       0.43000
    1.0000        0.0000     /
8500 'GENROU' 4    10.000     0.50000E-01   1.0000        0.50000E-01
    7.0000        0.0000       2.4200        2.0000       0.23000
   0.41080       0.17062      0.14812       0.10890       0.37795     /
8500 'STAB1' 4    10.000       3.0000       2.5000        0.20000
   1.0000        1.0000       0.1000 /
8500 'SCRX'   4    0.0000     0.40000E-01   10.000        0.40000E-01
    0.0000        5.0000       0.0000        0.0000     /
8500 'IEESGO' 4   0.10000E-01   0.0000      0.15000       0.30000
    8.0000       0.40000       0.0000       0.70000       0.43000
    1.0000        0.0000     /
8500 'GENROU' 5    10.000     0.50000E-01   1.0000        0.50000E-01
    7.0000        0.0000       2.4200        2.0000       0.23000
   0.41080       0.17062      0.14812       0.10890       0.37795     /
8500 'STAB1' 5    10.000       3.0000       2.5000        0.20000
   1.0000        1.0000       0.1000 /
8500 'SCRX'   5    0.0000     0.40000E-01   10.000        0.40000E-01
    0.0000        5.0000       0.0000        0.0000     /
8500 'IEESGO' 5   0.10000E-01   0.0000      0.15000       0.30000
    8.0000       0.40000       0.0000       0.70000       0.43000
    1.0000        0.0000     /
8500 'GENROU' 6    10.000     0.50000E-01   1.0000        0.50000E-01
    7.0000        0.0000       2.4200        2.0000       0.23000
   0.41080       0.17062      0.14812       0.10890       0.37795     /
8500 'STAB1' 6    10.000       3.0000       2.5000        0.20000
   1.0000        1.0000       0.1000 /
8500 'SCRX'   6    0.0000     0.40000E-01   10.000        0.40000E-01
    0.0000        5.0000       0.0000        0.0000     /
8500 'IEESGO' 6   0.10000E-01   0.0000      0.15000       0.30000
    8.0000       0.40000       0.0000       0.70000       0.43000
    1.0000        0.0000     /
```

APPENDIX E - WIND MODELING

The following model descriptions and figures are based on [59].

Generator/converter model

The generator/converter model is an equivalent of the generator and the full converter; hence it is the interface between the WTG and the network. The model is injecting real and reactive current in response to commands from controls and represents low and high voltage protection (e.g. low voltage ride through capability) [59]. The model is seen in Figure E- 1.

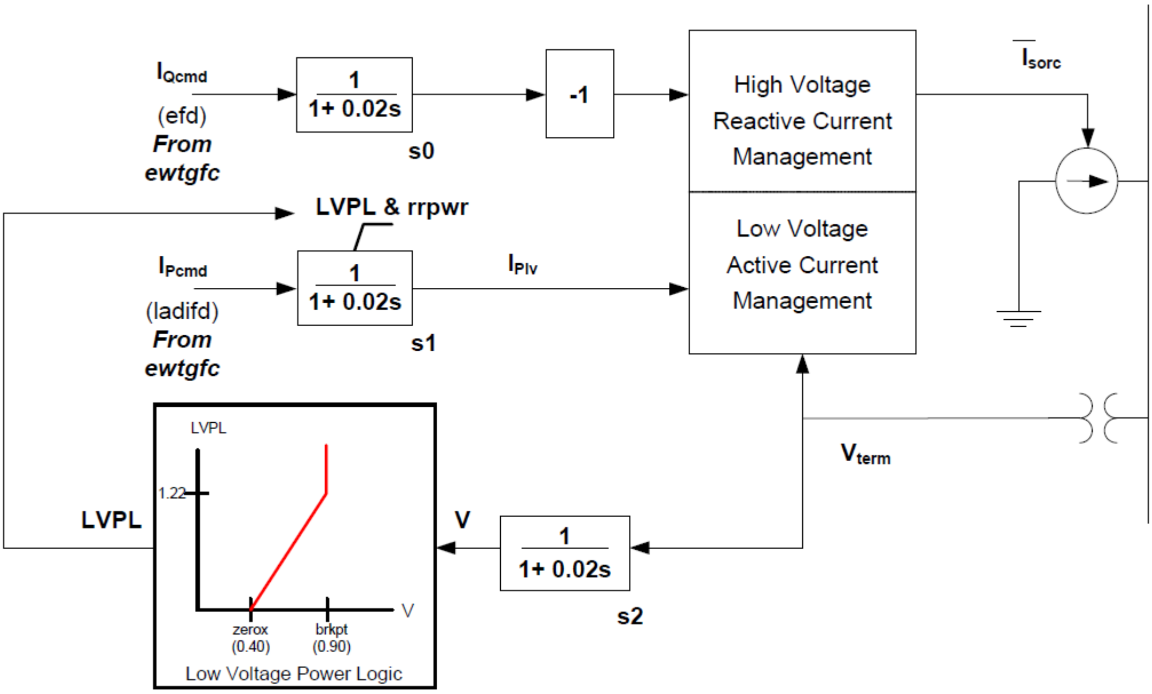

Figure E- 1: Generator/converter model [59].

Electrical (Converter) Control Model

The electrical converter control model gets inputs from the turbine model (P_{ord}) and the supervisory VAr controller (Q_{ord}) and will decide the active and reactive power that goes to the Generator/converter model. Q_{ord} can come from a separate model, the WindCONTROL model included in the electrical control model or it can be held constant or set by a power factor regulator [59]. The reactive power control model is depicted in Figure E- 2, the accompanying Q droop model is seen in Figure E- 3 and the final electrical control model is depicted in Figure E- 4.

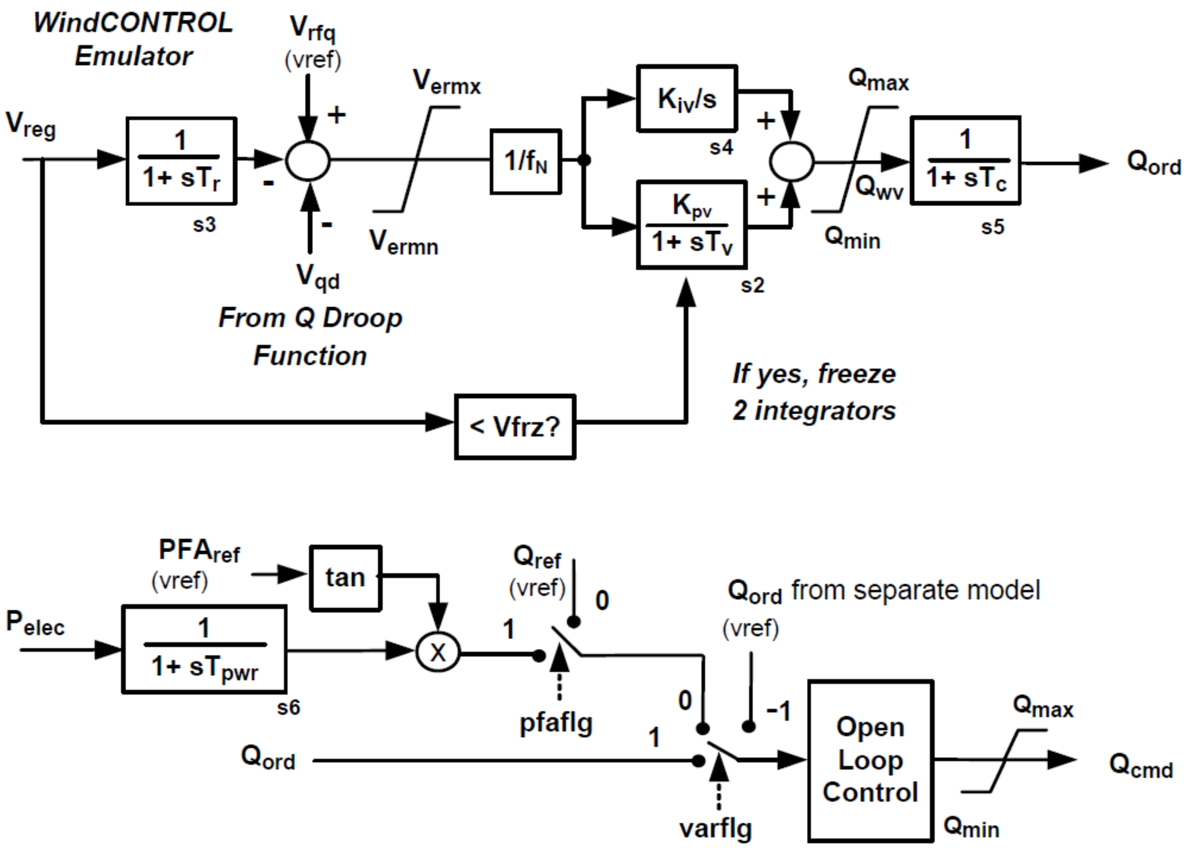

Figure E- 2: Reactive power control model - WindVAR emulator in GEWTE model [59].

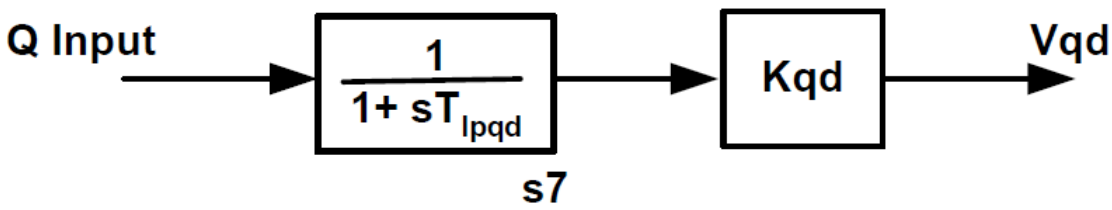

Figure E- 3: Q-droop function model [59].

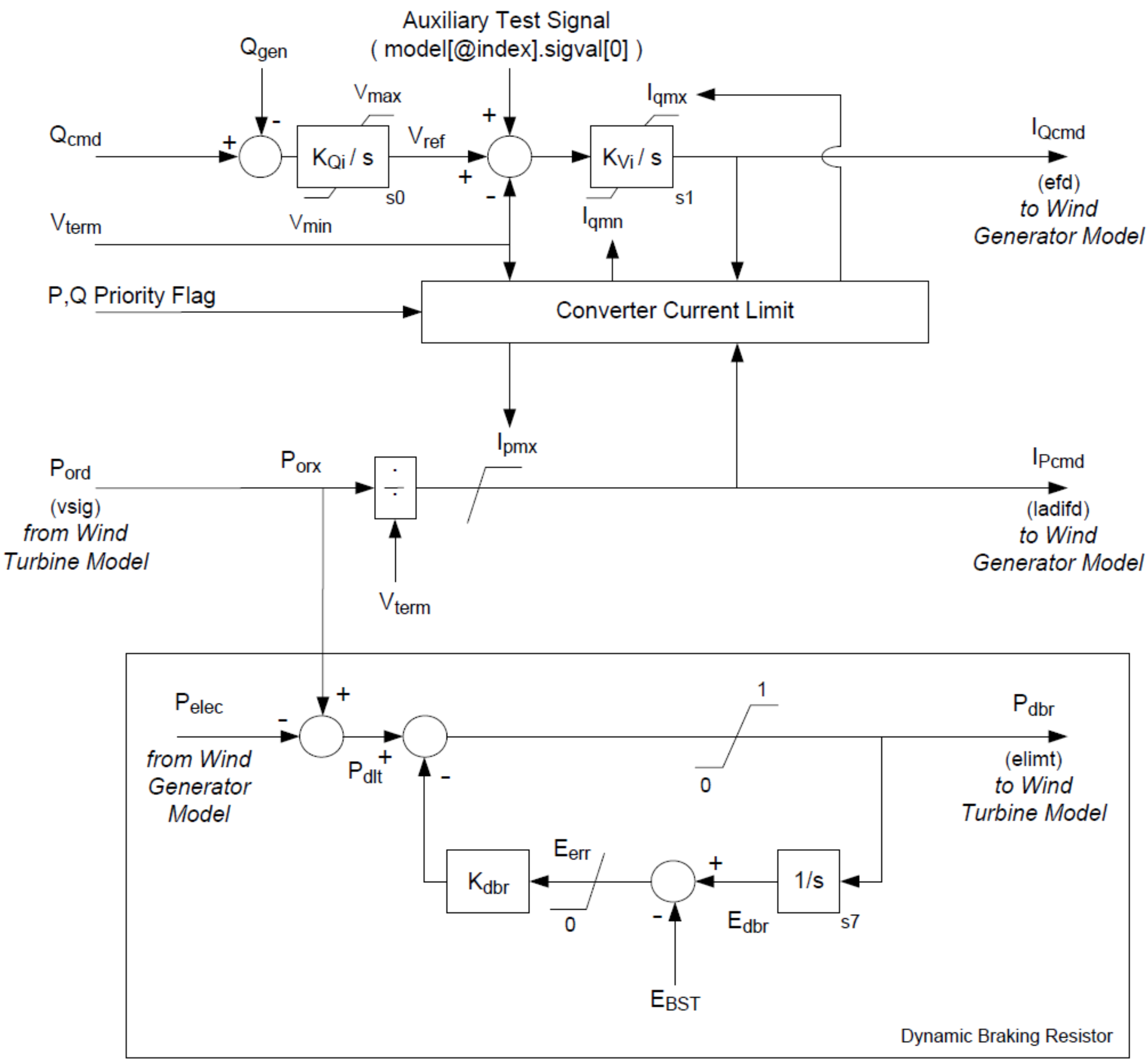

Figure E- 4: Electrical control model [59].

Turbine modeling

Wind power model

This model will compute the WT mechanical power from the energy in the wind using equation 5-1. The relationship between blade tip speed and turbine rotor speed is a fixed constant, K_b. ($\lambda=K_b(\omega,v_w)$).

Wind Rotor Model

The block comprises the rotor inertia equation for the WTG rotor. Mechanical power from the wind power model and electrical power from the generator/converter model are inputs and the equation will give out the rotor speed. Two options are available; single mass equivalent or two-mass model, where the first one is recommended.

Turbine control model – Pitch control and compensation

This model takes the speed order (ω_{ref}) and the P_{set} as inputs from the converter model, shaft speed ω from the turbine model and generated power from the load flow (pinp) and gives out the blade pitch (θ) to the turbine model. When available wind is above rated, the blades are pitched to limit the mechanical power, while when the wind is below rated the blades are minimum pitched to maximize mechanical power.

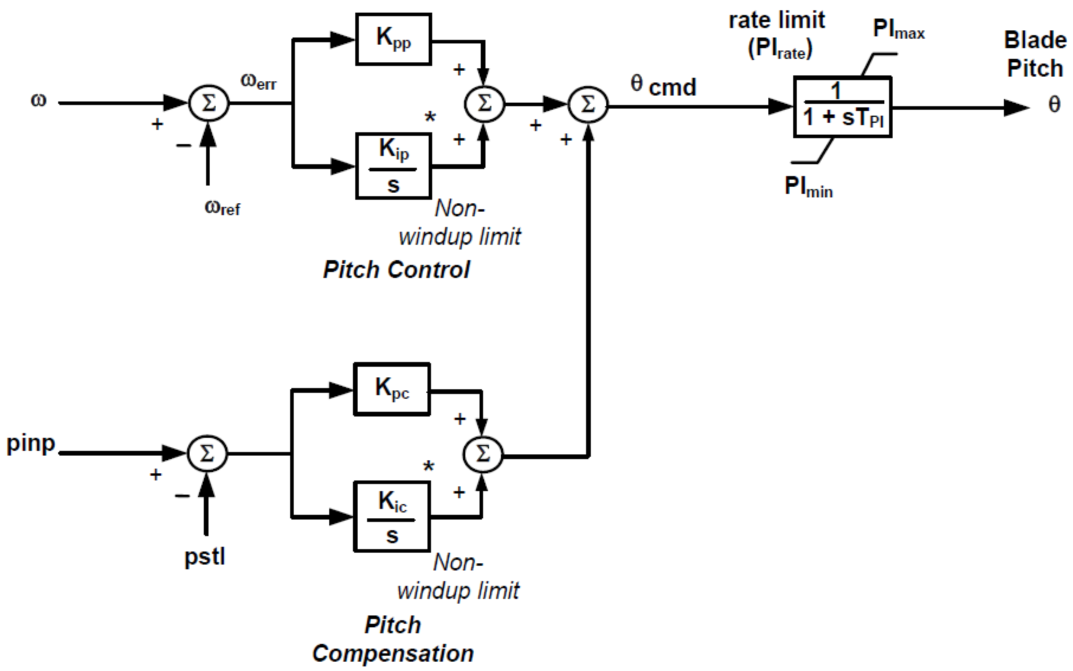

Figure E- 5: Pitch control and pitch compensation [59].

Active Power Control (APC)

APC is required by many European grid owners. The objectives of the control are to enforce maximum power output, provide a margin by generating less output then available, enforce ramp rate limits and response to frequency excursions.

By default the control is disabled (will be enabled by setting the apcflg=1). During normal operating conditions at nominal frequency the control will either give a maximum plant output (P_{max}) or generate less power and leave a margin by e.g. generate at 95 % of available power.

At a frequency excursion the control changes and will calculate a power order as a function of frequency. This means more power than regularly will be produced if the frequency is low and less power than regular will be produced if the frequency is high, as a response to loss of generation or load respectively. The model inputs are available power and terminal frequency. This is most efficient for reducing output at high frequencies (seen in Figure E- 7) since power curtailment is necessary to leave a margin for responding on low frequency events [59].

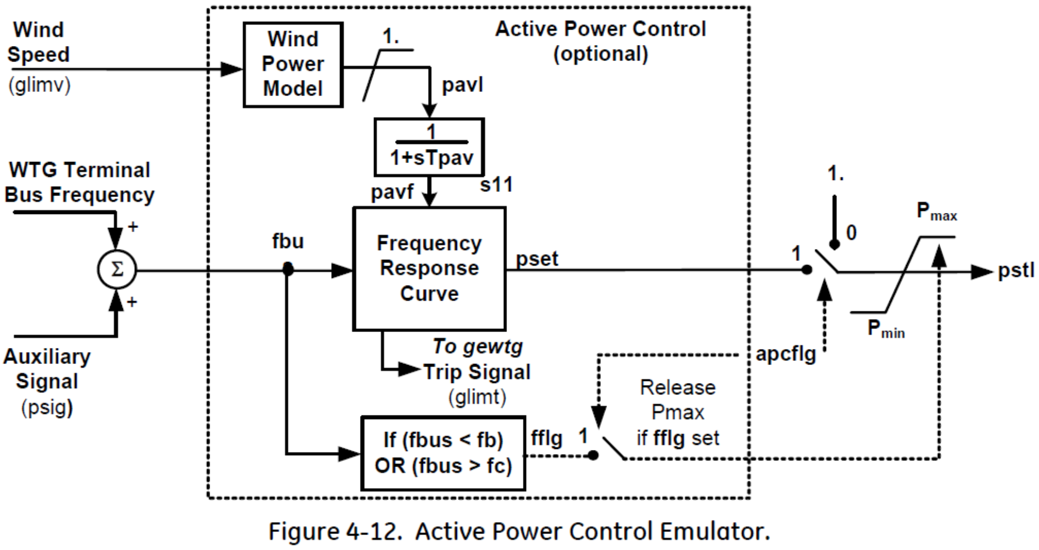

Figure E- 6: Active power control emulator [59].

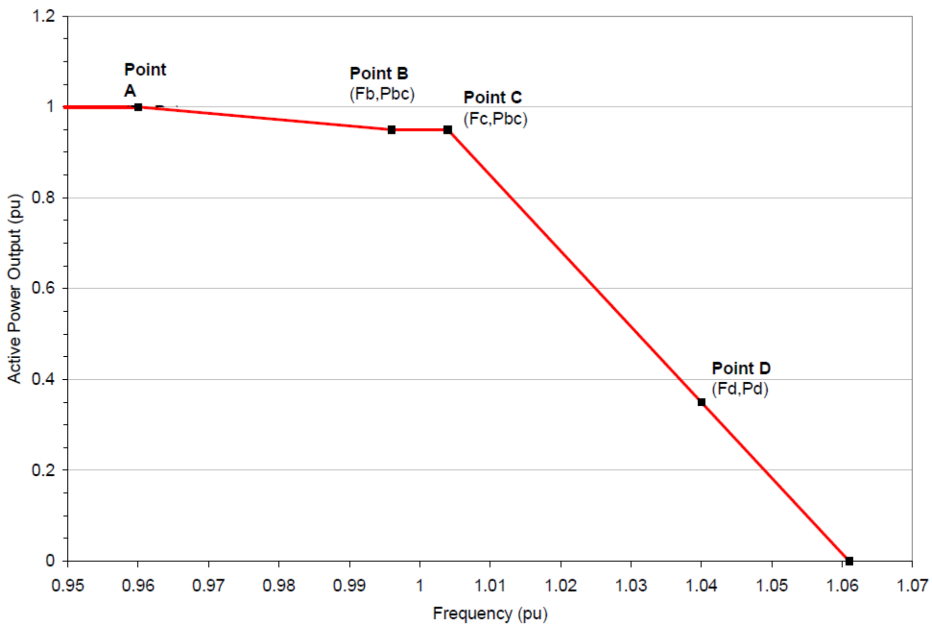

Figure E- 7: Example of frequency response curve [59].

Parameters (default values)

** GEWTG2 **

PRATE	XEQ	VLVPL1	VLVPL2	GLVPL2	VHVRCR2
4.0000	99999.0	0.4000	0.9000	1.2400	1.2000

CURHVRCR2	VLVACR1	VLVACR2	RIp_LVPL	T_LVPL	LVPL1V
2.0000	0.4000	0.8000	10.0000	0.0200	0.0000

LVPL1P	LVPL2V	LVPL2P	LVPL3V	LVPL3P	XLVPL
0.0000	0.5000	0.1670	0.9000	0.9250	0.0000

** GEWTE2 OF GEWTG **

TFV	KPV	KIV	RC	XC	TFP	KPP
0.1500	18.0000	5.0000	0.0000	0.0000	0.0500	0.3000

KIP	PMX	PMN	QMX	QMN	IPMAX	TRV
0.1000	1.1200	0.0000	0.4021	-0.4021	1.2400	0.0200

RPMX	RPMN	T_POWER	KQi	VMINCL	VMAXCL	KVi
0.4500	-0.4500	60.0000	0.1000	0.9000	1.1000	120.0000

XIQmin	XIQmax	Tv	Tp	Fn	TPav
0.5000	1.4500	0.0500	0.0500	1.0000	0.1500

FRa	FRb	FRc	FRd
0.9600	0.9960	1.0040	1.0400

PFRa	PFRb	PFRc	PFRd
1.0000	0.9500	0.9500	0.4000

PFRmax	PFRmin	TW	T_LVPL	V_LVPL
1.0000	0.2000	1.0000	0.2500	-1.0000

SPDW1	SPDWMX	SPDWMN	SPD_LOW	WTTHRES
14.0000	25.0000	3.0000	-0.9000	8.0000

EBST	KDBR	Pdbr_MAX
0.2000	10.0000	1.0000

ImaxTD	Iphl	Iqhl	TIpqd	Kqd	Xqd	Kwi
1.2200	1.1200	0.9000	5.0000	0.0000	0.0000	0.0000

dbwi	Tipwi	Twowi	urIwi	drIwi	Pmxwi	Pmnwi
0.0025	1.0000	5.5000	0.1000	-1.0000	0.1000	0.0000

Vermx	Vermn	Vfrz	QmxZP	QmnZP
0.1000	-0.1000	0.7000	0.4000	-0.4000

** GEWTT1 **

H	DAMP	Htfrac	Freq1	DSHAFT
5.1200	0.0000	0.0000	1.4500	1.5000

** GEWGD1**

T1G	TG	MAXG	T1R	T2R	MAXR
9999.000	5.000	30.000	9999.000	9999.000	30.000

** GEWTA2 **

Lambda_Max	Lambda_Min	PITCH_MAX	PITCH_MIN	Ta	RHO
20.0000	0.0000	27.0000	-4.0000	0.0000	1.2250

Radius	GB_RATIO	SYNCHR
50.0000	91.3000	1200.0000

** GEWTP2 **

Tp	Kpp	Kip	Kpc	Kic
0.3000	150.0000	25.0000	3.0000	30.0000

TetaMin	TetaMax	RTetaMin	RTetaMax	PMX
-4.0000	27.0000	-10.0000	10.0000	1.0000

APPENDIX F - SIMPLE TWO BUS SYSTEM TO TEST THE HYGOV MODEL

As trouble occurred when tuning the model a new and simple model was created for investigation. The purpose was to test the hydro governor model in a simple model, to verify that this model works as excepted. A two bus model with three generators and one load was created. Bus 1 is the swing bus and here is a thermal/nuclear generator located. At bus 101 there are a load, one hydro unit and one small thermal/nuclear to represent the unit that will be lost.

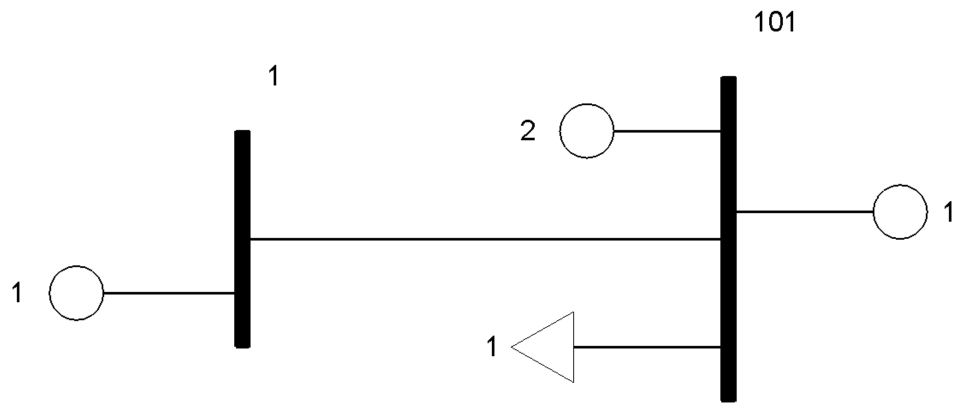

Figure F- 1: Simple test system

The model is approximately 1/5 scaled down in production and load compared to Scenario 1. Dynamic data are taken from the Nordic44 model, one random example on a hydro unit (Bus 5400) and one nuclear/other thermal unit (Bus 8500). The HYGOV data are as follows

Parameter	Value
$\rho_{PSS/E}$ (R in figure) – Permanent droop	0.145
r – Temporary droop	0.9
T_r – Governor time constant	3
T_f- Filter time constant	0.05
T_g – Servo time constant	0.8
VELM	0.2
G_{MAX}	1.0
G_{MIN}	0.0
T_w – Water time constant	1.3
A_t –Turbine gain	1.1
D_{turb} – Turbine damping	0
q_{NL} – No power flow	0.08

Table F- 1: Simple test system - Data for HYGOV-model.

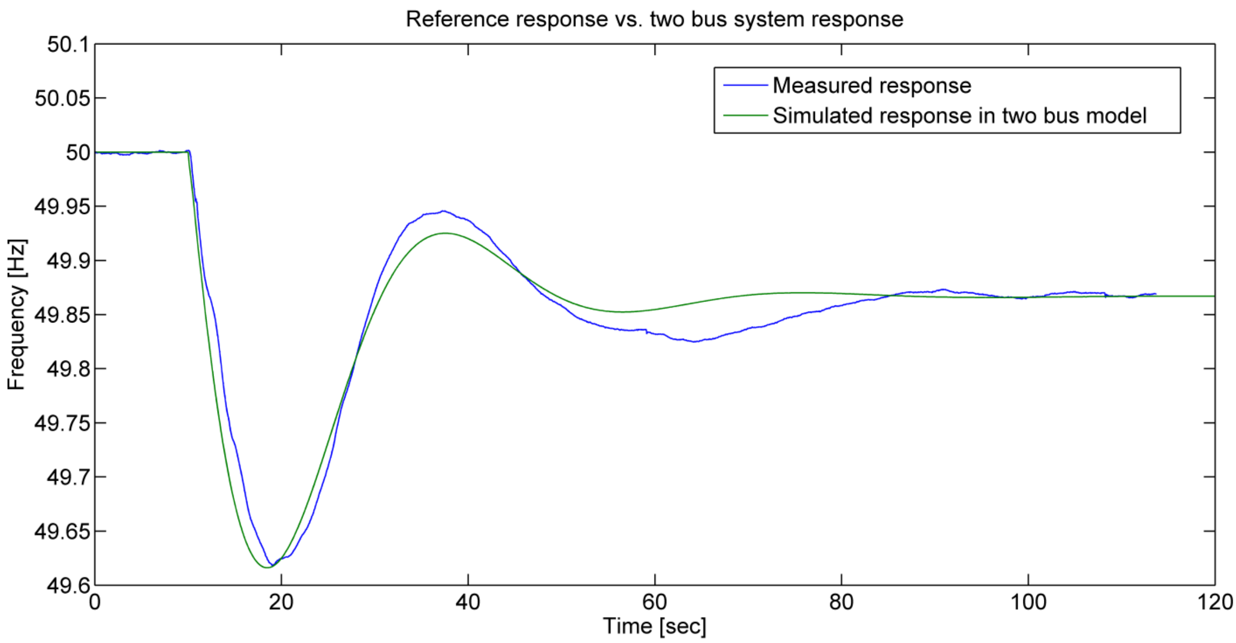

Figure F- 2: Reference response vs. response from simple test system.

This model was simulated with load division I/Y/P of 15/15/70 and the result verifies that there is no problem with the HYGOV-model. The mistake in Nordic44 must either come from the voltage dependence of the load or other dynamic modeling. Note that not much effort was put in tuning this model, as it is only used to prove the findings.