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Analysis of Slow Frequency Variations in the Nordic Power System

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Submission date: June 2014
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Abstract

Slow oscillations in system frequency, with a periodic time of 60-90 seconds and amplitude of 50 mHz, has been observed in the Nordic grid. As a result the frequency is outside the limit of 50 ± 0,1 Hz more often. It is assumed that this cause wear on turbines and generators. It may also cause additional activation of balancing power in the Regulating Power market, and impose an additional cost on the transmission system operators (TSOs). Together, the Nordic TSOs have worked on a report evaluating causes and mitigation of the problem. One of the suggestions is to improve the tuning of the hydro turbine governors.

In this Master Thesis a model of the Nordic grid has been used for simulations in PSS/E (Power System Simulation for Engineering), and the effect of governor tuning has been evaluated. In addition, a Simulink model has been developed based on data in the PSS/E model, in order to be able to run longer simulations without having numerical problems. The objective was to find out whether changing the governor parameters, or other system parameters, may reduce the problem of low-frequent oscillations. Spectral analysis of the simulated frequency has been used to determine the periodic time of the frequency variations. The modeled frequency responses are similar to the real life frequency response, which confirms that the models are valid for frequency analysis. Simulations run with random load changes, and with different governor settings, indicated that the periodic time and amplitude of the frequency variations are affected by the governor parameters R_p, R_t and T_r. The inertia in the system also has a great impact on the periodic time and variance of the frequency oscillations. Deadbands were implemented on the governors in the Simulink model, and they were found to amplify the amplitude of the oscillations, and to make the periodic time longer.

Sammendrag

Målinger viser at systemfrekvensen i det nordiske kraftnettet svinger med en periodetid på 60-90 sekunder. Amplituden er typisk på 50 mHz. Disse langsomme svingningene gjør at frekvensen oftere befinner seg utenfor området på 50 ± 0,1 Hz, og det antas at den fører til slitasje på turbiner og generatorer. Det vi også gjøre at mer regulerkraft fra regulerkraftmarkedet aktiveres, og dette er en kostnad for de systemansvarlige selskapene. Statnett og de andre systemansvarlige i Norden har gått sammen for å se på mulige årsaker og muligheter til å forbedre situasjonen. Innstillingene på turbinregulatorene er en av tingene de nevner som kan forbedres.

I denne masteroppgaven har en PSS/E-modell (Power System Simulation for Engineering) av det nordiske kraftsystemet blitt brukt til å undersøke effekten av å endre på regulatorinnstillingene. En Simulink-modell har blitt utviklet i tillegg, basert på verdier fra PSS/E-modellen, for å kunne kjøre simuleringer over lengre tid uten å støte på numeriske problemer. Målet med arbeidet har vært å se om endring av regulatorparametrene kan redusere problemet med de langsomme svingningene. Spektralanalyse av simulerte frekvenssignaler har blitt brukt for å fastslå periodetiden til frekvensvariasjonene. Det har blitt vist at frekvensen i den forenklede modellen oppfører seg tilnærmet likt som den virkelige frekvensen, ved å sammenligne simulert respons med en ekte hendelse. Ulike simuleringer med tilfeldige lastendringer, kjørt med ulike regulatorinnstillinger, tyder på at periodetiden til frekvenssvingningene påvirkes av verdiene til regulatorparametrene R_p, R_t og T_r. Tregheten i systemet påvirker også frekvenssvingningene i stor grad. Dødbånd ble lagt til på regulatorene i Simulink-modellen, og simuleringene har vist at de forsterker amplituden på svingningene. I tillegg gjorde de periodetiden lengre.

Preface

This Master's Thesis has been carried out at the Department of Electric Power Engineering at the Norwegian University of Science and Technology (NTNU) during the spring semester of 2014. The project was initiated by my supervisor professor Kjetil Uhlen, who has been part of the TSO (Transmission System Operator) work group that addresses the problem of slow variations in system frequency in the Nordic grid. I would like to express my gratitude for all help and support he has given me. I also want to thank Din Thuc Duong for helping me with PMU measurements.

Trondheim, 2014-06-12

Anja Oftebro

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Chapter 1

Introduction

1.1 Background

The Nordic power system consists of numerous interconnected producers and consumers located in Norway, Sweden, Finland and Eastern Denmark. As electric power must be consumed at the same time as it is produced, there will always be stability issues in the power grid. The power balance is the responsibility of the transmission system operator (TSO) in each country. The Nordic TSOs have to work together closely to keep the system in synchronized and balanced operation.

There is observed a marked oscillation in frequency of 11-25 mHz, and this have a negative impact on the frequency quality in the Nordic power system. It is assumed that the oscillations cause wear on components in the grid. The Nordic TSOs have worked together to produce the report "Measures to mitigate the frequency oscillations with a periodic time of 60-90 seconds in the Nordic synchronous system" [1]. It states that the typical amplitude of this frequency oscillation is 50 mHz. The amplitude varies from night to day, from weekday to weekend, and from winter to spring to summer. There has been an increase in the variance of the oscillations over the last 15 years wile the mean value has remained constant. As a result the frequency will be outside the limit of 50 ± 0,1 Hz, defined in the Nordic Grid Code [2], more frequently.

In addition to improve the frequency quality, there is also an economic motivation for studying the frequency floating phenomena; tuning the turbine regulators in a way that reduces the frequency deviation will reduce the need of balancing power, and this will reduce the socio-economic cost. Power producers are paid for having synchronized power available that can obtain the instantaneous balance in case of a mismatch between production and consumption. This power is sold on the Nordic Regulating Power market, and the TSOs are the buyers.

Problem Formulation

Slow variations/oscillations in system frequency (typically with a periodic time of 60-90 seconds) can be observed in the Nordic power system. This has a negative impact on the frequency quality and is thus a concern for the Nordic TSOs.

The main hypothesis is that these oscillations are related to turbine controls and dynamics in the hydraulic systems and possible adverse interactions between units. A system approach will be taken to analyze which parameters contribute to create these oscillations, and which parameters that can be tuned to damp the oscillations.

1.2 Objectives

The main objectives of this Master's project are

1. To simulate the slow frequency oscillations in the Nordic power grid.
2. To analyze the effect of hydro turbine governor tuning.
3. To analyze which parameters contribute to the oscillations.

1.3 Structure of the Report

The rest of the report is structured as follows. Chapter 2 gives an introduction to the theory of power system stability and control. Chapter 3 is a literature survey of the topic, and Chapter 4 contains an analysis of PMU recordings. In Chapter 5 the different simultion tools and the specific models used for simulations are presented. Chapter 6 goes through the steps in the procedure of simulations, which results are presented in Chapter 7. In the final chapter, Chapter 8, the results are summed up and conclusions are drawn.

Chapter 2

Theory

2.1 Power System Stability

In *Power System Dynamics* [3], power system stability is defined as the ability to regain an equilibrium state after being subjected to a physical disturbance. There will always be contingencies, and the system should be controlled in a way that reduces the damage and consequences of unexpected events. The subject can be divided into rotor angle stability, frequency stability and voltage stability. Equations 2.1 and 2.2 describe the active and reactive power flow in the system as functions of voltage, reactance and power angle. E and V are the voltages on each side of a transmission with impedance X. δ is the angle between them, as illustrated in Figure 2.1.

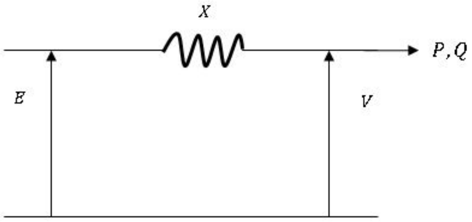

Figure 2.1: Simplified model of a grid element. Figure taken from [3].

$$P = \frac{EV}{X} \sin\delta \tag{2.1}$$

$$Q = \frac{EV}{X} - \frac{V^2}{X} \tag{2.2}$$

The voltages can be kept constant while changing the active power. It is then only dependent on the power angle, δ, which again is dependent on the system frequency. Imposing a change in reactive power flow will cause the voltage to change. When controlling a power system all quantities, and the way they affect each other, must be taken into consideration. Protection schemes may give structural changes after a disturbance and aggravate the stability situation.

2.2 Linear Analysis

A linear system can be described by the state matrix, **A**, and the state vector, **x**, which includes all the state variables of the system. In many cases, a non-linear system can be linearized around an operating point. For a power system the linear analysis will be valid when analyzing a small disturbance. The further away from the operating point, the more inaccurate the linear representation will be.

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} \tag{2.3}$$

Equation 2.3 has the solution:

$$\mathbf{x}(t) = e^{\mathbf{A}t}\mathbf{x}_0. \tag{2.4}$$

2.2.1 Eigenvalues

In Equations 2.5 and 2.6 λ is the eigenvalue of the eigenvector υ.

$$\mathbf{A}\upsilon = \upsilon\lambda \tag{2.5}$$

$$(\mathbf{A} - \lambda\mathbf{I})\upsilon = \mathbf{0} \tag{2.6}$$

A solution to Equation 2.7 is an eigenvalue λ_i.

$$det(\mathbf{A} - \lambda\mathbf{I}) = 0 \tag{2.7}$$

The eigenvalues can be real, or they can have both a real and an imaginary part as demonstrated by Equations 2.8 and 2.9.

$$\lambda_i = \sigma_i \tag{2.8}$$

$$\lambda_i = \sigma_i \pm j\omega_i \tag{2.9}$$

2.3 Control Theory

Transfer functions are mathematical models of linear physical systems; they describe the relation between the input and the output of the system in the frequency domain. If a step input is applied to the system, the system will respond to this, and the response can be observed in the output signal. If U is the step input, the stationary step response will be $K \cdot U$. K is the steady state gain of the system, and describes the relation between the input and the output of the system. Once a regulator is added to the system, the eigenvalues will be different, and also the system response. The stationary deviation may be decreased, or a time delay may appear, or if the eigenvalues are placed wrongly the system may go from stability to instability. Bode diagrams are used to analyze the amplification and phase difference of the output signal, for different frequencies.

The poles of the transfer function, given by the eigenvalues, describe the stability of the system. A complex pole with a positive real part causes oscillations that result in instability. With all complex poles on the left side of the imaginary axis there will be oscillations, but they will be damped and stability is achieved. When all the poles are real there will be no oscillation.

Marginal stability is possible when a pole is on the imaginary axis, and results in a constant oscillation as stated by Balchen, Andresen and Foss in [4].

2.4 Swing Equation

An unbalanced torque on the rotor will lead to acceleration or deceleration according to Newton's second law (Equation 2.10). The system inertia constant, J, and the damping torque coefficient, D_d, determine how much the rotor shaft speed, ω_m, will change when there is an unbalanced torque. A change in speed, means there is a change in frequency, and Equation 2.10 is the starting point for understanding frequency changes in a power system. The deduction of the equations in this section follows the one by Machowski, Bialek and Bumby in [3] p.169-172.

$$J\frac{d\omega_m}{dt} + D_d\omega_m = \tau_t - \tau_e \tag{2.10}$$

The steady state torque balance is given by Equation 2.11. τ_e is the electromagnetic torque, and τ_t is the sum of τ_e and the damping torque. When in balance, the electromagnetic torque equals the mechanical torque, τ_{mech}.

$$\tau_t = \tau_e + D_d\omega_m\tau_{mech} = \tau_t - D_d\omega_{synch} = \tau_e \tag{2.11}$$

Here, ω_m is the rotor shaft speed in [rad/s], whereas ω_{synch} is the synchronous speed of the system. The relation between the two is described by Equation 2.12. δ_m is the rotor angle in mechanical radians, and $\frac{d\delta_m}{dt}$ is the speed deviation in [rad/s].

$$\omega_m = \omega_{synch} + \frac{d\delta_m}{dt} \tag{2.12}$$

The resulting expression in Equation 2.13 is obtained by substituting ω_m in Equation 2.10 with Equation 2.12.

$$J\frac{d^2\delta_m}{dt^2}+D_d\frac{d\delta_m}{dt}=\tau_m-\tau_e \tag{2.13}$$

$$P=\tau\times\omega \tag{2.14}$$

In terms of shaft power, P_m, and electrical air-gap power, P_e, Equation 2.13 can be written as Equation 2.15. In Equation 2.15 D=$\omega_{synch}D_d \times p/2$, where p is the number of poles. The inertia constant H is defined as the stored kinetic energy of the rotor at synchronous speed in [MJ], divided by the machine rating in [MVA]. The relation in Equation 2.14 is used to get from torque, τ, to power, P, and shows that power and frequency are two directly connected properties.

$$2H\omega\frac{d\omega(t)}{dt}=(P_m(t)-D\Delta\omega(t)-P_e(t)) \tag{2.15}$$

Equation 2.15 is equivalent to Equation 2.16 in the frequency domain (s-domain). This equation is visualized in Figure 2.2.

$$\Delta\omega(s)=\frac{1}{2Hs}(P_m(s)-D\Delta\omega(s)-P_e(s)) \tag{2.16}$$

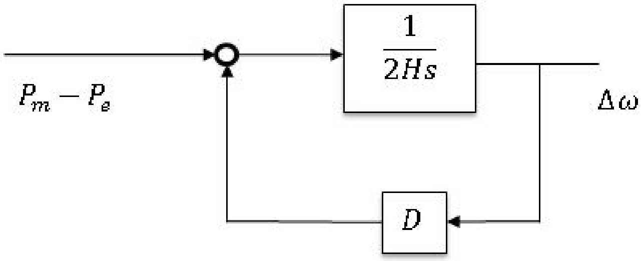

Figure 2.2: Block diagram of Equation 2.16, the swing equation.

2.5 Hydro Turbine Governor

An ideal governor keeps the speed deviation equal to zero or a pre-defined value. Aiming on the reference value, the governor increases or decreases the gate opening (the input to the hydraulic system). The gate opening lets a certain amount of water spin the turbine, which in turn delivers a mechanical torque to the generator. Following Newton's second law (Equation 2.10), the inertia of the system affects how fast the speed of the rotor will change when there is an unbalance in torque. When the electrical loading increases, the rotational speed (frequency) will go down. Figure 2.3 is a sketch of how the power flows in the power system: how a difference in load and production will lead to a change in frequency, and how it is controlled by the governors.

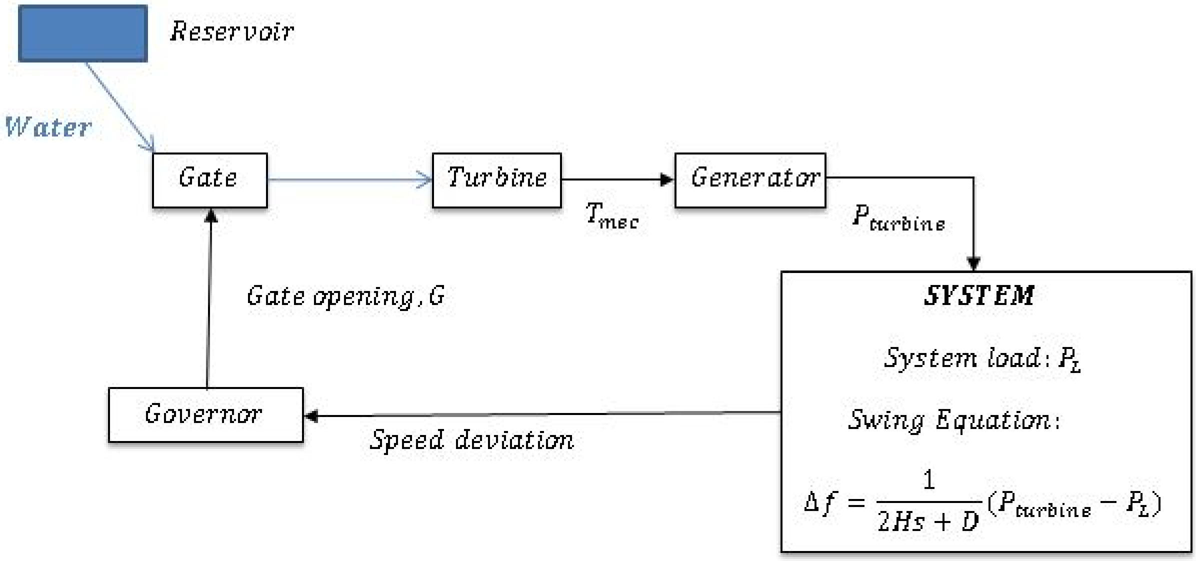

Figure 2.3: Power system sketch. Water is let in to the turbine through a gate, governed by a governor. The spinning turbine has a mechanical torque that is transformed to electrical power by the generator. The swing equation describes how the frequency is changed when the power produced by the turbines in the system does not equal the system load. Speed deviation is the input the governor uses to determine how much water should spin the turbine.

$$\Delta G = -\frac{1}{R_p}\Delta\omega \tag{2.17}$$

In steady state, the gate opening, G, is changed according to Equation 2.17. It can vary from 0 to 1, and by doing so the power will either go up or down. The change in power output, ΔP_m, can be expressed by $\frac{\Delta P_m}{\Delta P_n} = \Delta G$. When writing in terms of frequency instead of speed ($\omega = 2\pi f$) the equation becomes:

$$\frac{\Delta f}{f_n} = -R_p \frac{\Delta P_m}{P_n} \tag{2.18}$$

R_p is the permanent droop, and is the gradient of the power-speed characteristics in Figure 2.4. A small droop ensures that a change in load only causes a small change in the frequency. This is desirable from the TSO's point of view, whereas the producers prefer a higher droop setting so that a change in frequency only causes a small change in the production. For a hydro turbine governor the speed-droop coefficient is typically 0,04-0,12.

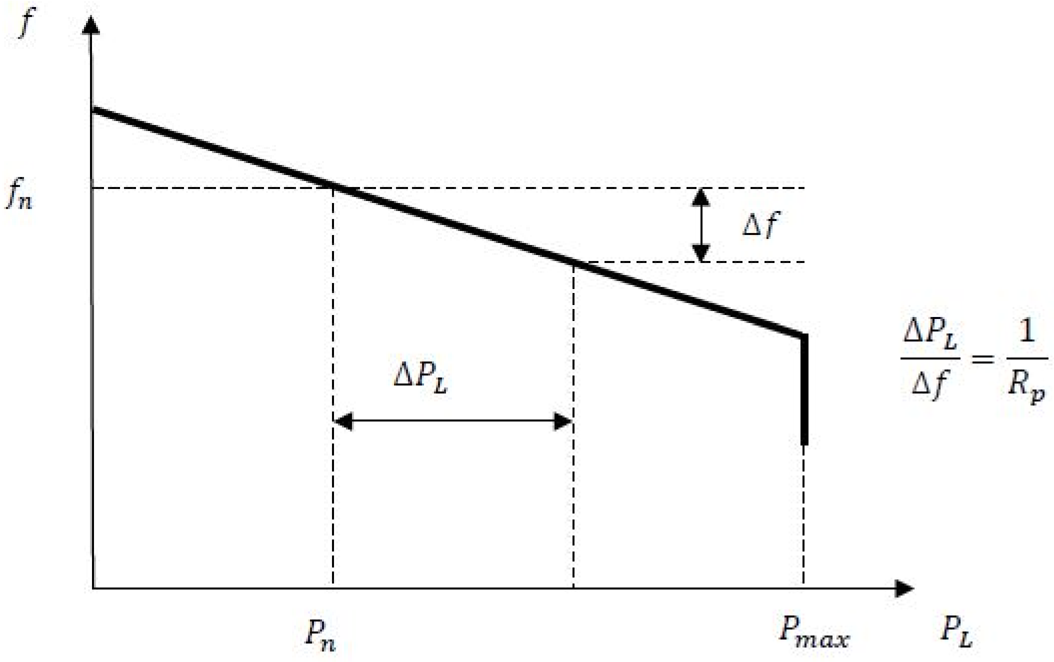

Figure 2.4: Steady state speed-droop characteristics. The permanent droop parameter, R_p, determines how much the power production changes after a change in frequency.

The regulator is only effective until it reaches complete gate opening, or when produced power equals the maximum value of the unit. The difference between the total delivered power and total maximum delivered power, from the synchronized generators in the system, is the "spinning reserve". With no spinning reserve there is no regulating power available to increase the frequency immediately after a disturbance.

The transient droop regulates the change in frequency that follows a change in power, before it reaches the stable value described by the permanent droop. It limits the overshoot during the transient state. A typical value of R_t is 0,4 [3].

Although modern governors are electronic and use PI(D) controllers (Proportional-Integral-Derivative controller), the linear model presented in Figure 2.5 is widely used. It is often referred to as the "classical governor" and has the most essential characteristics of the turbine governor. It is sufficient for most modelling purposes.

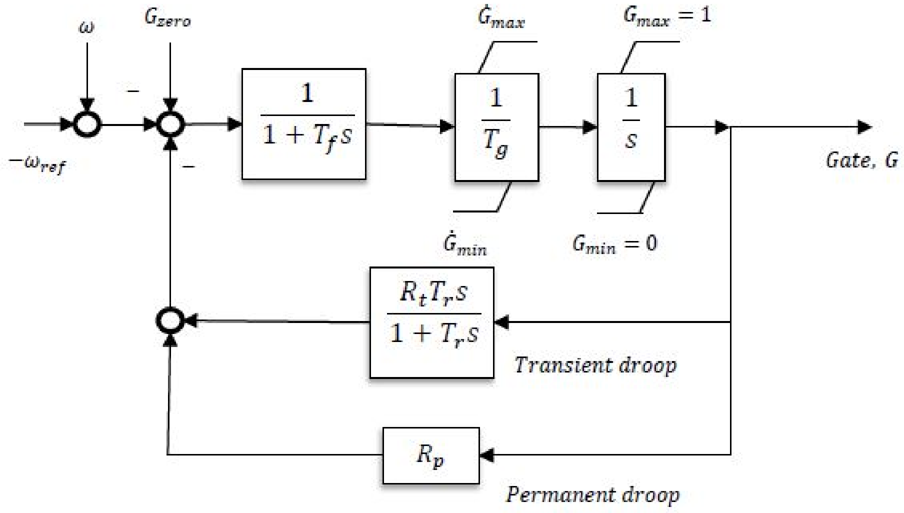

Figure 2.5: Classical governor from *Power System Dynamics* [3].

The transfer function of the classical governor in Figure 2.5 is given by Equation 2.19.

$$\frac{\Delta G}{\Delta \omega} = \frac{\frac{(1+T_r)}{R_p}}{\frac{T_f T_r T_g}{R_p} s^3 + \frac{(T_f+T_r)T_g}{R_p} s^2 + \frac{T_g+T_r(R_p+R_t)}{R_p} s + 1} \tag{2.19}$$

As the filter time constant, T_f, is small it can be neglected. The third order transfer function of Equation 2.19 then reduces to the second order transfer function of Equation 2.20.

$$\frac{\Delta G}{\Delta \omega} = \frac{(1+T_3 s)K}{(1+T_2 s)(1+T_4 s)} \tag{2.20}$$

In Equation 2.20 $K = \frac{1}{R_p}$, $T_2 \approx \frac{T_r T_g}{T_g + T_r(R_p+R_t)}$, $T_3 = T_r$, and $T_4 = \frac{T_g + T_r(R_p+R_t)}{R_p}$.

The hydraulic system/turbine can be represented by the transfer function of Equation 2.21, with T_w being the water time constant.

$$\frac{1 - T_w s}{1 + 0{,}5 T_w s} \tag{2.21}$$

An even simpler PI controller is presented in Figure 2.6, and its transfer function can be studied in Equation 2.22. It is included to demonstrate the parameters effect on the resulting gain from the governor for different frequencies, as the effect will be approximately the same for the "classical governor". Figure 2.7 illustrate the resulting gain from the governor when exposed to different frequencies. The proportional gain, K_p, is the inverse of the transient droop, R_t, and it will be the effective governor gain for frequencies larger than $\frac{1}{T_i}$. T_i corresponds to T_r, and decreasing it means that the proportional gain region is shifted towards higher frequencies. The steady state gain, K, is given by $\frac{1}{R_p}$.

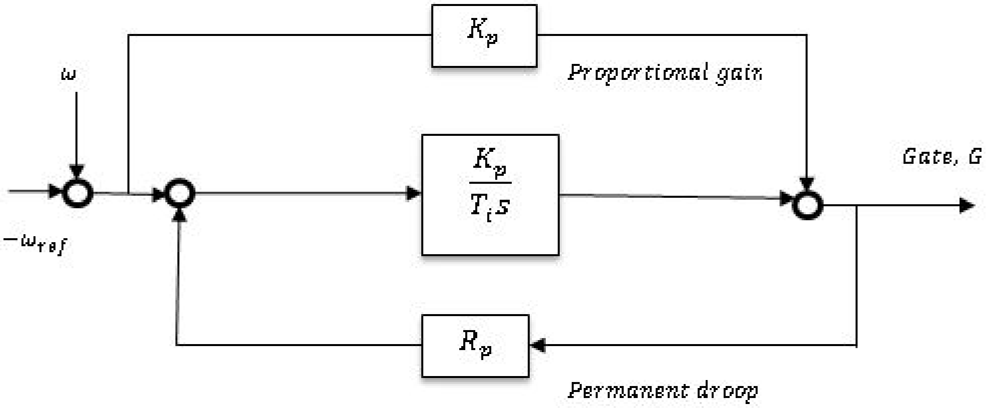

Figure 2.6: Block diagram, simple PI controller.

$$\frac{\Delta G}{\Delta \omega} = K_p \frac{(1 + T_i s)}{(T_i s + K_p R_p)} \tag{2.22}$$

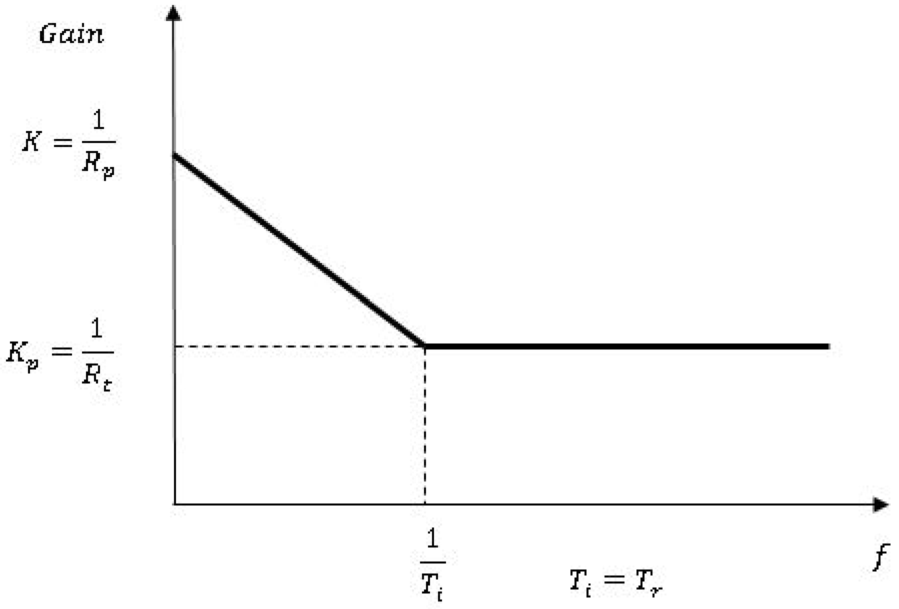

Figure 2.7: Governor gain for different frequencies, for the simple PI controller of Figure 2.6. K_p is the gain for frequencies larger than $1/T_i$. K is the steady state gain (zero frequency).

2.6 Frequency Control

Frequency control is executed in three steps: primary, secondary and tertiary control. ENTSO-E (European Network of Transmission System Operators for Electricity) operate with the term FCP (Frequency Containment Process) for the three steps of frequency control [5]. Primary control is performed automatically by the turbine governor and leads to a frequency deviation. The secondary and tertiary control is merged in the Nordic regulating market. Usually the secondary control (Automatic Generation Control) brings the frequency back to normal (f_n=50 Hz), by activating reserves. Then, during the tertiary control, the reserves activated during secondary control are freed (manually). The ENTSO-E terms for primary, secondary and tertiary control are FCR (Frequency Containment Reserves), FRR (Frequency Restoration Reserves) and RR (Replacement Reserves). The time frame of FCR and FRR is 15 minutes for the Nordic Regulating Power market, and within these minutes all the reserves should be activated if there is need for them. It can take up to hours for the RR to be activated.

The further away from the maximum or minimum production point a power plant is operating, the more power it has available to regulate the frequency. All production units have a droop setting that decides how much the power will change when the frequency changes. From a producers point of view the droop should be high; they do not wish the power production to change as the frequency varies. For the grid as a whole it would be inconvenient if a change in power made the frequency deviate more than necessary from its rated value. The individual permanent droop setting of a producing unit decides how much regulating power it will contribute with, in relation to all the other units, in case regulating power is needed.

When dealing with a system consisting of more than one production unit, it is convenient to have the linear approximation of the generation characteristics for the total demand. The deduction that follows corresponds to the one by Machowski *et. al* in [3] p.336-338.

$$\frac{\Delta f}{f_n} = -R_{p,tot}\frac{\Delta P_T}{P_L} \tag{2.23}$$

In Equation 2.23, ΔP_T is the total change in production for all units summarized, and ΔP_L is the total loading of the system. The permanent droop for the total system, $R_{p,tot}$, is calculated by Equation 2.24. K_T in Equation 2.25 is the [MW/Hz] response for changes in production.

$$R_{p,tot} = \frac{\Delta f}{f_n}\frac{P_L}{\sum_i^{N_G} P_{mi}} \tag{2.24}$$

$$K_T = \frac{1}{R_{P,tot}} \tag{2.25}$$

Every load connected to the system will also be frequency dependent. For the total system load the characteristics is given by Equation 2.26.

$$\frac{\Delta P_L}{P_L} = K_L\frac{\Delta f}{f_n} \tag{2.26}$$

The sum of K_L, the load frequency response, and K_T is denoted K_f and is known as the stiffness of the system. The frequency response in [MW/Hz], is given by this coefficient. A change in demand will give a frequency change described by Equation 2.27.

$$\Delta P_{demand} = \Delta P_T - \Delta P_L = K_f P_L \frac{\Delta f}{f_n} \tag{2.27}$$

2.7 Spectral Analysis

Spectra are functions of frequency. The power spectral density function (PSD) in Equation 2.28 is given by Brown and Hwang in *Introduction to Random Signals and Applied Kalman Filtering* [6].

$$S_X(j\omega) = \int_{-\infty}^{\infty} \mathrm{R_X(t')e^{-j\omega t'}}\,\mathrm{d}t' \tag{2.28}$$

The power spectral density is the Fourier transform of the autocorrelation function (Equation 2.29). It describes the relation between the frequency and the power of a sinusoidal varying signal, and can be used to identify whether the signal varies periodically or not. White noise has no periodicity, the signal contains all visible frequencies, and as a consequence it has a constant power spectral density function.

Autocorrelation function:

$$R_X(t_1', t_2') = E[X(t_1)X(t_2)] \tag{2.29}$$

Expected value of X:

$$E(X) = \int_{-\infty}^{\infty} \mathrm{xf_x(x)}\,\mathrm{d}t' \tag{2.30}$$

If the mean value and variance do not change over time, the signal is stationary, and the autocorrelation is only dependent of the time difference t', t_2'-t_1'.

Example 1

$fs = 1000;$

$t = 0 : 1/fs : 5 - 1/fs;$

$x = cos(2 * pi * 100 * t) + randn(size(t));$

The power spectral density estimate of the cosine plotted in 2.8, is plotted in Figure 2.9. It is obtained by the Matlab function pwelch(). The example below demonstrates how the power spectral density function catches the most apparent frequencies in the signal. There is a peak at 100 Hz, while rest of the spectrum which reflects the random noise, is flatter.

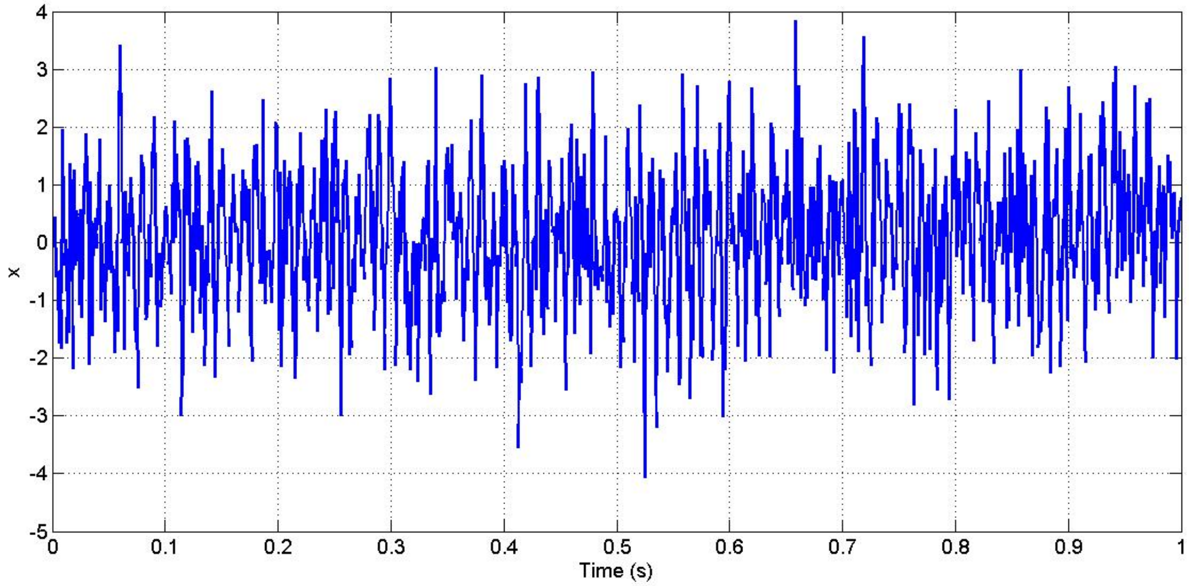

Figure 2.8: Cosine wave of Example 1, x = cos(2*pi*100*t)+noise.

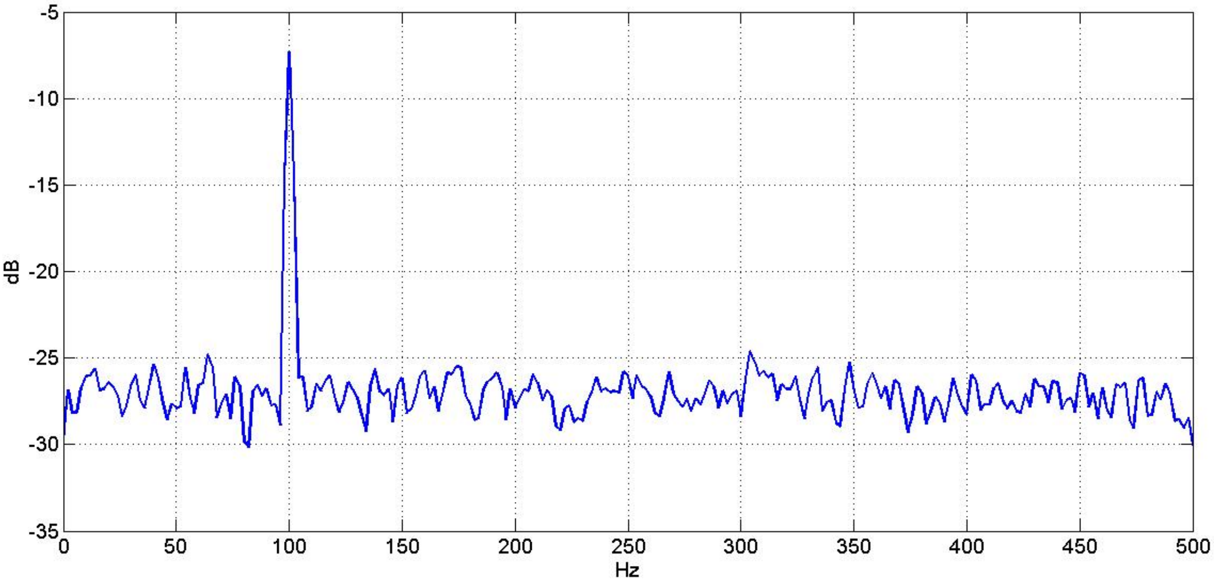

Figure 2.9: Power spectral density estimate of x in Example 1.

2.8 Effect of Deadband on Frequency Control

Several production units in the Nordic power system are implemented with deadbands, in order to reduce the wear on the generators. The position of the governor control valve is not changed unless the frequency deviation is bigger than the deadband. A deadband adds non-linearity to the system, and makes any linear approximation of the non-linear governor model more invalid. This makes the optimization progress of the governor parameters more complex. One effect of governor deadband is that the effective speed regulation, R_p, is increased, this was first shown by Concordia *et. al* [8] in 1957. They also concluded that speed governor deadband tends to destabilize the system, and may produce oscillations.

Adding deadbands to generators is a way of deciding which units that should be part of the primary frequency control. If the deadband is large enough the governor will take no action. The TSO work group use the term FNR (frequency controlled normal reserve) to describe the reserves activated within the range of 50 ±0,1 Hz [1]. Generators with larger deadbands will release extra reserves for more severe disturbances when the frequency is outside this range. This is referred to as FDR (frequency controlled disturbance reserve). ENTSO-E has the term Frequency Restoration Control Error Range (FRCE Range). FNR will be activated within the Level 1 FRCE Range, and FDR when the frequency is in the Level 2 FRCE Range [5].

Chapter 3

Findings by the TSO Work Group

In this chapter the findings of the TSO work group in [1] will be presented. As stated in the introduction chapter, the frequency in the Nordic grid varies with a marked period of 40-90 s, and the amplitude of the variations can be up to 0,05 Hz. "Amount of oscillations" is defined as [Hz·s]. The amount of oscillations is high when the frequency is far away from its normal value over a long period. High amplitude and high periodic time on the frequency variations will result in a high amount of oscillations. To reduce the amount of oscillations, both the periodic time and the amplitude should be lower.

3.1 Identification of Changes in the Grid

The problem of frequency variations is increasing, and thus the work group have identified recent changes in the grid to see what may cause the problem. As a result of increased variance, the frequency is outside its limits more often. Figure 3.1 supports this conclusion. There is a trend that the total system inertia is lower, and contributing factors are refurbished hydro power production units, and more loads connected through adjustable speed drives. Lately, FNR (Frequency controlled Normal Reserve - activated within 49,9-50,1 Hz) is delivered from fewer units, and there are less reserves in the system as a whole.

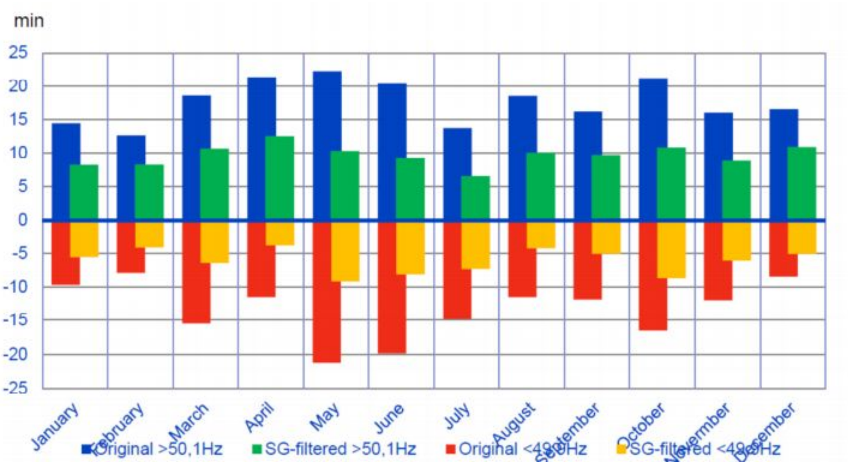

Figure 3.1: Duration of frequency above 50.1 Hz and below 49.9 Hz for every month in a year (2007). Figure taken from [1].

3.2 PMU Analysis

Phasor Measurement Units (PMUs) measure the electrical waves in the grid (phasors). PMUs are synchronised with GPS time, and this increases the accuracy of the measurements. The work group has performed an analysis based on PMU measurements, to categorize the frequency oscillation amplitude and periodic time during a day, a week, and over years. They conclude that the oscillations are lowest during winter time and high production. The amount of oscillations is highest during spring time and the flood period. The problem of low-frequent oscillations is also less during summer vacation time, and during night time and Sundays. The work group found the amount of oscillations to be larger around the hour shifts, which is associated with load adjustments in the system. Over the last years, the variance of the oscillations has increased, but the mean value has stayed constant. Correlation between the PMU measured variations and sold frequency reserves, FNR, have been investigated, and it was found that the oscillations may be affected by which producer that delivers the FNR.

3.3 Linear Analysis and Time Domain Simulations

Correlation between production and frequency variation gives reason to think that it is power oscillations that is the triggering of the frequency oscillations. Linear analysis performed by the work group explains that it is natural that frequency oscillations will occur in a system if a periodic power variation is applied on the system.

Time domain simulations with deadbands on all hydro generators done with the RAR model described in [1] p. 42, gave the work group the plot in Figure 3.2. It indicates that the governor deadband amplifies frequency oscillations. The frequency oscillations will increase in amplitude and the highest frequency amplitude will appear at higher oscillatory periods.

It is found that an increase in the proportional part of the PI controller ($K_p = \frac{1}{R_t}$) reduces the frequency oscillations. An increase in the time constant of the integrating part in the turbine governor decreases the resonance frequency, but the change in oscillation amplitude is small. Running simulations while changing parameters, it was also found that all deadbands should be removed and there should be more FNR in the system in order to reduce the frequency oscillations. The FNR should be spread out on as many units as possible. More kinetic energy in the system, and more frequency dependency of the loads, will contribute to reducing the amount of oscillation.

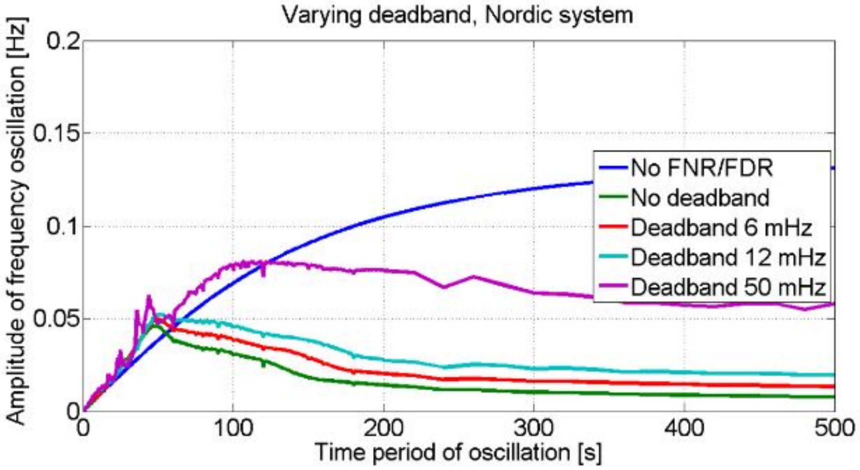

Figure 3.2: Effect of varying the deadband on all units in the Nordic system [1].

3.4 Tests at Hydro Power Units

The work group did tests on hydro power stations to check what the actual dynamic and stationary stiffness K_f in [MW/Hz] of the production units is. The frequency response when exposed to periodic frequency oscillations (dynamic frequency response) varies with the periodic time of the oscillations, and for a period of 60 s, it was found to be 10 times lower than the stationary frequency response. There were large differences between the test units. It was also discovered that some producers do not know the exact settings of their governors, and that FNR specifications are interpreted differently by the producers. The tests revealed that the units contribute to damping of frequency oscillations having periods larger than 30-70 s, whereas the amplitude of the frequency oscillations becomes higher for with periods less than 30-70 s.

Chapter 4

Analysis of PMU recordings

4.1 PMU recordings

As a part of the STRONGrid project (Smart Transmission Grid Operation and Control), PMUs have been installed at several Nordic universities. The PMUs are synchronized with GPS time, and this gives very accurate measurements. The PMU in Aalto, Finland, from which the frequency sample used for this study is collected, transmits 50 measurements per second.

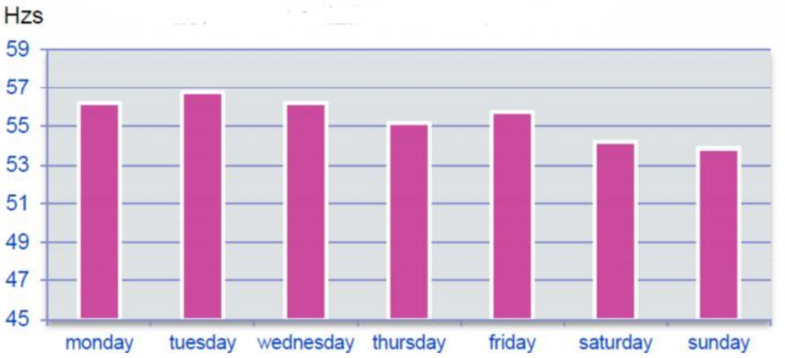

Figure 4.1: Amount of oscillation and during different weekdays 2011. Figure taken from [1].

4.2 Analysis of PMU data

The TSO work group behind [1] found that the oscillations generally are lower during night time and Sundays. Figure 4.1 is a plot of Aalto PMU measurements, and is meant to demonstrate the

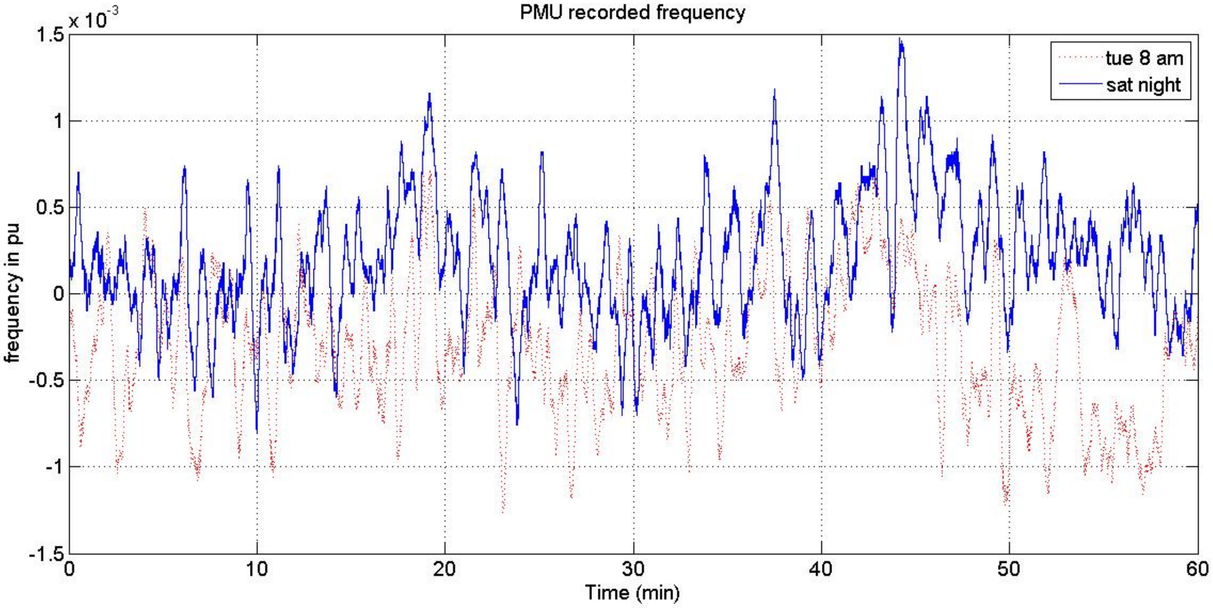

Figure 4.2: One hour Aalto PMU recorded frequency in pu (per unit = frequency/nominal frequency), started at: Tuesday 18.02.14 08:00 (red dotted line), Sunday 23.02.14 04:00 (blue line). $1 \cdot 10^{-3}$ pu = 50 mHz.

differences between the weekdays. Recordings from 8 am Tuesday was compared with recordings from Sunday morning 4 am, to find out whether the same differences in frequency variations could be found. From findings of the work group, it was expected that the slow oscillations in frequency would be more apparent in the week day recordings than in the ones from the weekend during nigh time.

The typical low-frequent oscillations have a time period of 40-90 s and an amplitude up to 0,05 Hz ($1 \cdot 10^{-3}$ pu). The measurements should have the same characteristics. Figure 4.2 shows that the amplitude is sometimes a little larger, but the number of peaks per 10 minutes matches the 40-90 s range.

It is hard to draw any conclusions solely from the power spectra of Figure 4.3, other than that these are largely random variations. Measurements from one week may not be not enough to see the general tendency.

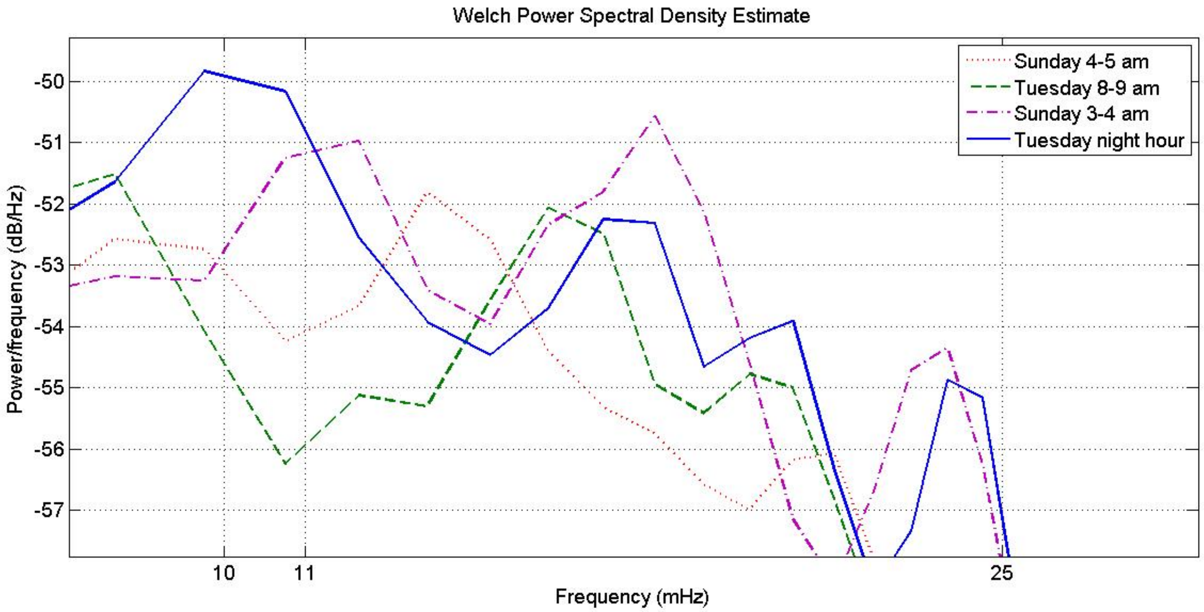

Figure 4.3: Welch Power Spectrum Density Estimate of PMU frequency recordings from different hours during Tuesday 18.02.2014 and Sunday 23.02.2014. The green dotted line is the only day time hour, the rest are night hours.

Chapter 5

Simulation Tools and Models

Two different simulation tools will be used in the following chapters to simulate the frequency variations in the Nordic grid, and will be presented in this chapter. The Simulink model is based on the more extensive PSS/E model, made by Sintef. Both models are based on the system dynamics described in the theory chapter.

5.1 PSS/E

PSS/E (Power System Simulation for Engineering), by Siemens, is a powerful tool used for modeling, design, planning, and general analysis of a power transmission system. Both steady-state and dynamic analysis can be performed. The basic grid elements are pre-coded and can be connected in a one-line diagram, and important parameters can be changed from their pre set values to analyze the performance. The steady-state load flow must be solved in order to do a dynamic simulation. After a dynamic simulation has been executed, plots can be generated by PSS/E, or the results can be exported to be plotted in other programs.

5.1.1 Model Description PSS/E

The model used in this work has been developed at SINTEF Energy Research. It is a simplified representation of the Nordic power system, with 23 generators, and is described more detailed in [10]. The system is divided into geographical areas. The one-line diagram can be studied in Appendix B.4. Hydro generators in Sweden and southern Norway have the largest share of the power production, and they provide the regulating power in the Nordic area. Finland is represented by one hydro and one thermal plant, and Eastern Denmark by one thermal plant only. The governor for the hydro units in the grid is of a type called HYGOV and have the parameters listed in Table 6.1. Bus “5101” at Hasle, physically located close to the middle of the grid, is where the frequency has been observed for all simulations.

5.2 Simulink

Simulink is Matlab’s system simulation tool. The graphical programming with block diagram representation makes it easy to monitor the variables you are interested in.

5.2.1 Model Description Simulink

All the 15 hydro generators from the PSS/E model were included in the Simulink model. The rated machine production values, M_{base}, from the PSS/E model were used to scale the load production, with respect to S_{base} (1000 MVA). S_{base} = 1000 MVA is the base value used to calculate production and load in pu (per unit). Values for all system parameters are listed in Appendix B.1.

$$\frac{1}{2Hs+D} \tag{5.1}$$

$$H = \frac{\sum_{i}^{N_G} H_i M_{base,i}}{S_{base}} \tag{5.2}$$

The classical governor, described in Chapter 2.5, was implemented as a Simulink block with a turbine represented by the water time constant (see block diagrams from Matlab in Appendix B.2). The input is the speed, and the output is the mechanical power. The scaled (pu) mechanical power enters the system. The slow dynamics of the system are modeled by the simple block of Eq. 5.1. As a result of this simplification, all generators swing in phase with each other at low frequencies. The total inertia constant H for the system was summed up for all the generators (not only hydro generators), again using values found in the PSS/E model. The equation used for this calculation was Equation 5.2. Figure 5.1 shows a principal sketch of the model.

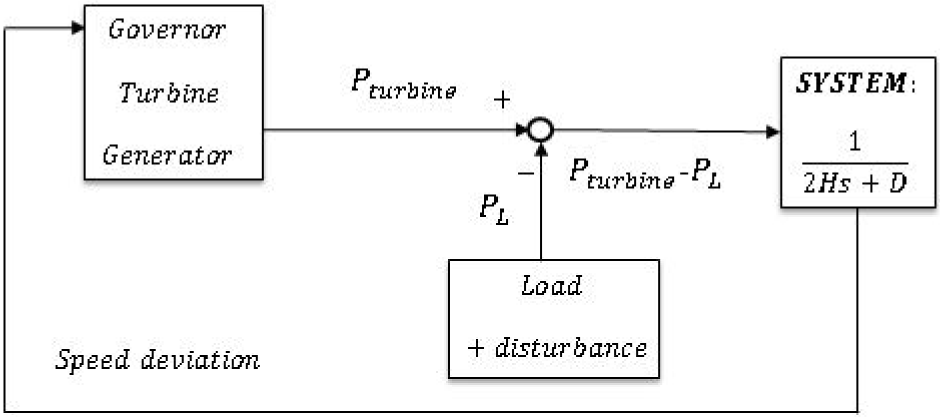

Figure 5.1: Principal sketch of Simulink model. The system in modeled by the simple block $1/(2Hs+D)$. A power imbalance triggers a frequency deviation, which is the input to the governor.

Chapter 6

Procedure of Simulations

First, the models in PSS/E and Simulink were tuned, and a validation was performed. Then a load situation with random variation was established to excite frequency oscillations. For the PSS/E model this was implemented in a Python script (Appendix B.6). The script makes the load change randomly, at random places, within given limits and a given time interval. The Simulink model can have either a time series object containing random changes, or a white noise block, as input to the load summation point. Finally, the method of trial and error is used to investigate the effect of tuning the hydro turbine governors, with the goal of reducing the amount of frequency oscillation.

6.1 Validation

An event from 11.06.2011, when a nuclear power plant in Sweden producing about 900 MW was suddenly disconnected, is used to verify and tune the model. In Figure 6.1 the event can be seen as the green dotted line. The load and production situation is recreated, and the hydro governor parameters are adjusted to make the simulated response fit the one observed in the real life system after the event 11.06.2011. The permanent droop is tuned individually for Norway and Sweden, based on the assumption that the Swedish governors generally allow a higher permanent frequency droop. In Table 6.1 the governor parameters that made the simulated responses fit the real life response the most are listed.

To simulate this particular event in the PSS/E model, hourly data from Nord Pool Spot [9] was gathered to scale down the load and production in Norway and Sweden, respectively. The M_{base} values were adjusted in accordance to this, using the rule of thumb $M_{base} = \frac{P_{gen}}{0,75}$. Because of lower demand there are fewer power producing units connected to the grid in summer. As a result there is less regulating power available, and the frequency is stabilized further away from the nominal value. Machine “3359, 2”, a thermal plant located west in Sweden, is producing 900 MW when disconnected at t = 1 s.

When tuning the Simulink model to make the frequency response curve fit the one from the 11.06.2011 event, the load and production was not scaled as it was not accurate to begin with. The total load in the system was set to 30 000 MW, and for the validation a step change of 900 MW was applied.

Table 6.1: Tuned parameter values for the turbine governor.

Parameter	PSS/E Best Fit	Simulink Best fit
Permanent droop, Rp, Norway	0,08	0,1
Permanent droop, Rp, Sweden	0,1	0,1
Transient droop, Rt	1,35	0,5
Governor time constant, Tr	2,6	4,3
Filter time constant, Tf	0,05	no filter
Water time constant, Tw	1	1
Servo time constant, Tg	0,2	0,2

6.2 Load Changing Scheme

The goal of the load changing scheme is to simulate the frequency variations detected in the real life system. The limits for maximum load change and maximum time step were chosen, considering that the typical amplitude of the simulated frequency variations should not exceed the typical amplitude of the PMU measurements in Figure 4.2.

For the PSS/E model a Python script was made to change the load value at the six largest loads in the system. The load bus is selected randomly. The size of the load change is random, within

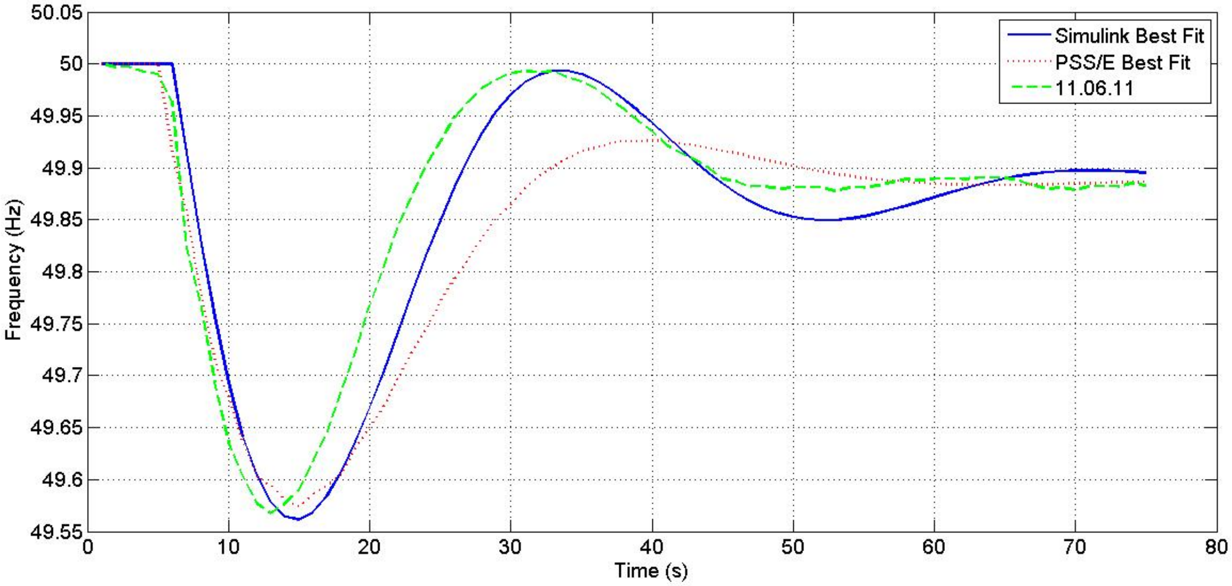

Figure 6.1: Frequency response of the PSS/E model (blue line) and the Simulink model (pink line) with their Best Fit governor parameters from Table 6.1 when loosing 900 MW production. Plotted together with real life event from 11.06.2011 (green line).

boundaries given as an input. An interval within which the simulation time increases randomly must also be specified. The maximum interval between load changes was set to 5 s, and the maximum load change to ± 50 MW. This gave the frequency response most similar to the PMU measurements. In Figure 6.2, the total loading on the six buses where the script changes the load is plotted. The total simulation time was set to 10 min to be able to see the long periodic times more clearly. Not all the simulations run with the load changing script can be expected to be successful. Running the script will sometimes give apparently meaningless results, especially when the governor parameter values are pushed to their limit. Simulations of several minutes are on the limit of the scope of PSS/E, and some numerical problems are expected. This is why the Simulink model was made: to be able to avoid these numerical problems.

In the Simulink model a time series object can be added to the load summation point, making the load change by ± 0,05 pu (± 50 MW), in time steps of 0-5 s. For unknown reasons these changes do not result in the same variations in frequency as they did in the PSS/E model. A Band-Limited White Noise block, with noise power equal to 0,01, sample time equal to 0,1, and

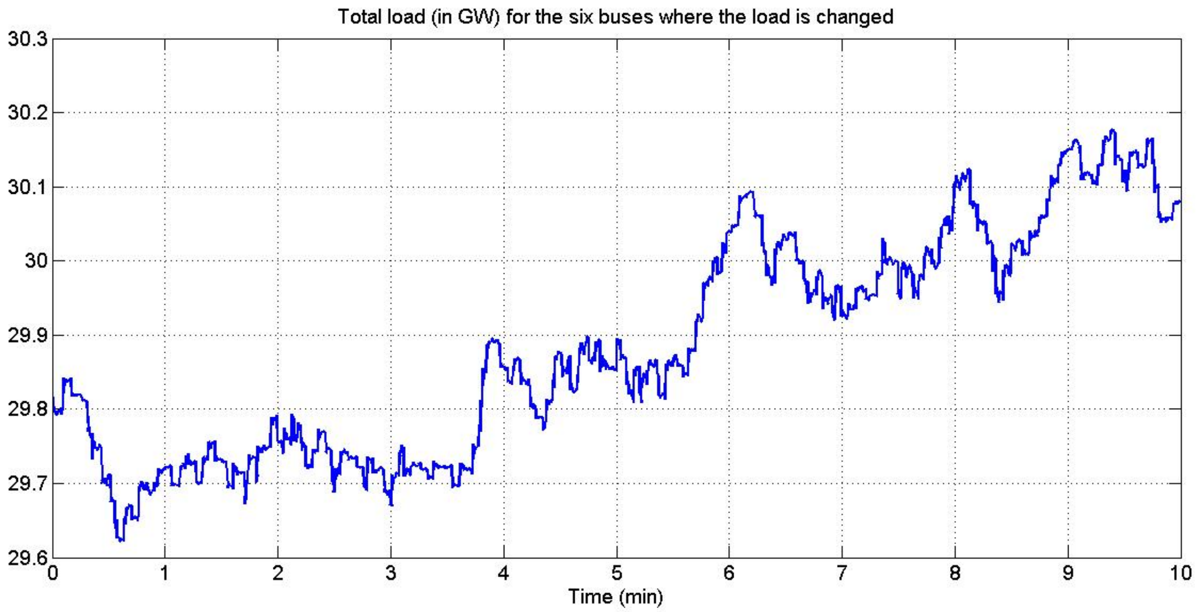

Figure 6.2: Total load at the six largest load buses in PSS/E model, picked randomly by the Python script in B.5. dL = 50 MW and dt = 5 s.

with a seed of [floor(rand × 100000)], gives frequency variations more like the PMU measurements, when added to the load going via a transfer function with a time constant of 2 s. This input will be different every time the simulation is run. This is also the case for the Python script for simulations in PSS/E. When analyzing the effect of parameter changes, the effect is more apparent when the input signal is equal every time the simulation is run. This is an advantage of using the load change time series as load disturbance. The load disturbance inputs from the white noise block and the time series object are plotted in Figure 6.3. The power spectra of the two schemes are plotted in Figure 6.4. The spectra reveal that the load changes in the time series object have a flatter spectrum, and behave more like white noise than the White Noise block going through the transfer function $\frac{1}{2s+1}$. See Figure 6.5 for the differences in frequency variation for different load inputs.

The imitation of the frequency variations is not perfect, neither in the Simulink model or in the PSS/E model. There is always room for improvement of the load changing scheme, and it can never be a perfect representation of the real life load changes. Although the period of the oscillations is too small compared with the one observed in the Nordic system, it is reasonable

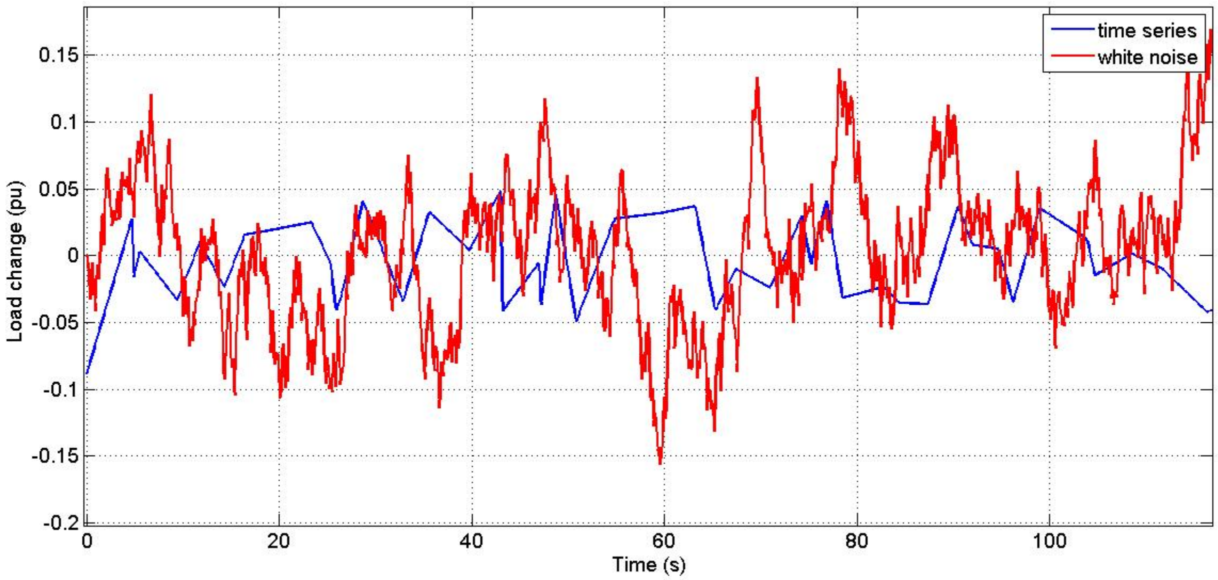

Figure 6.3: Load disturbance input to the Simulink model: white noise block via transfer function, and time series object with dL and dt equal to 50 MW (0,5 pu) and 5 s, as in the Python script for the PSS/E model.

to expect that the governor parameters' effect on the variations will be the same for more low-frequent oscillations.

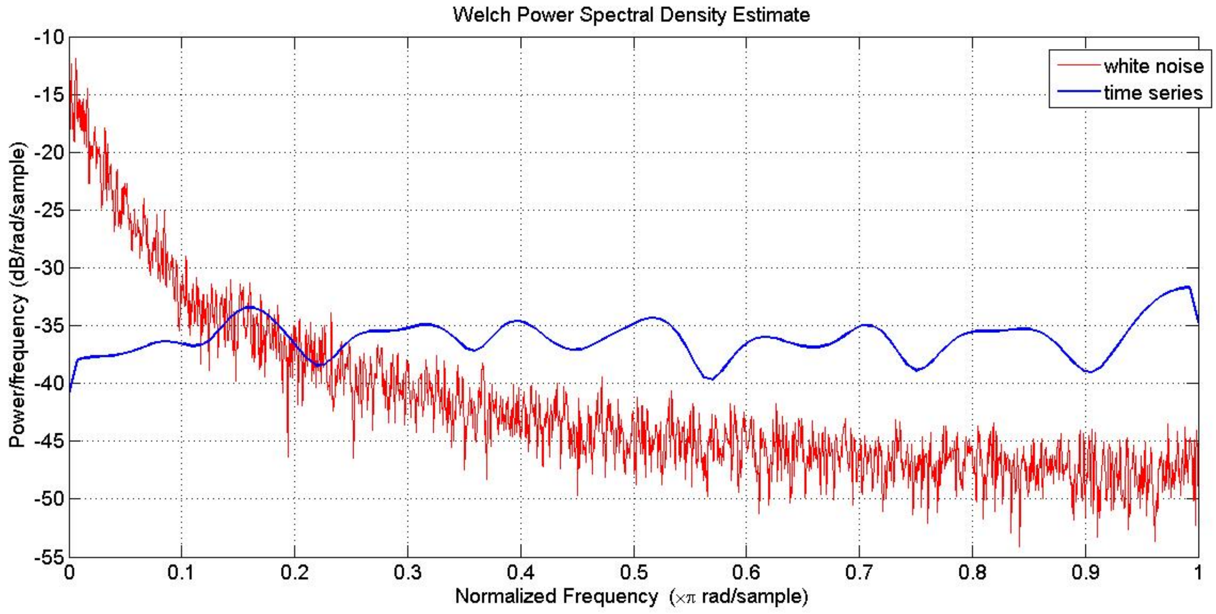

Figure 6.4: Welch power spectral density estimate of the load changing schemes in the Simulink model.

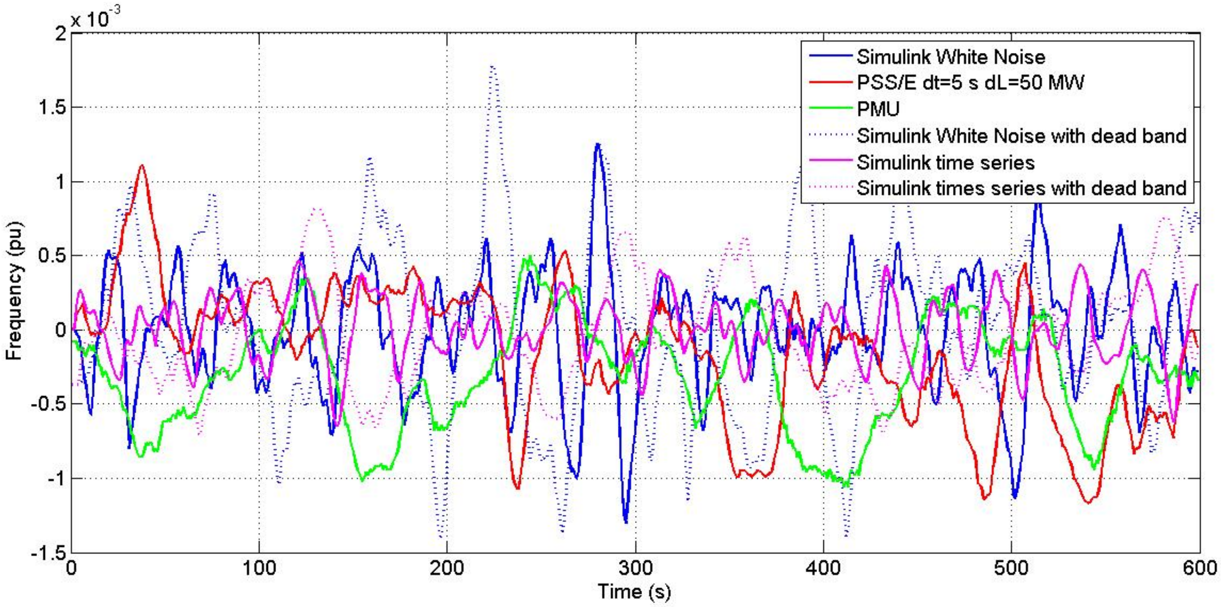

Figure 6.5: Frequency response of the PSS/E model and the Simulink model with their Best Fit governor parameters. The Simulink model is subjected to different load changing schemes, with and without deadbands of 0,0005 pu (0,025 Hz) on the generators. A PMU recording from 2014-02-18 is included for comparison.

6.3 Introducing a Deadband

To investigate the effect of the deadband non-linearity, the Simulink governor is modified so that it includes a deadband. The Dead Zone block in Simulink was used for this purpose, and the size of the limits of the band was set to $\pm 0,0005$ pu. See Table 6.2 for Dead Zone block functionality. The PSS/E model has no deadbands on the governors. The effect of the deadband can be seen in Figure 6.5, and will be commented further in Chapter 7.3.

Table 6.2: Matlab Dead Zone block: input vs. output.

Input	Output
lower limit < f < upper limit	0
f < lower limit	f - upper limit
f > upper limit	f - lower limit

6.4 Change of Governor Parameters R_p, R_t and T_r

The main goal of this thesis is to find out whether the hydro governors can be tuned in a way that reduces the low frequency oscillations observed in the Nordic power system. The parameters R_p, R_t and T_r are changed individually in both models, and the time domain plots and power spectra of the frequency signal produced by the respective load changing schemes are analyzed. For the analysis, the parameters are given the values listed in Table 6.3. The values are not necessarily realistic parameter values, they were chosen to demonstrate the effect of an increase or decrease.

Table 6.3: Turbine governor parameter changes. The parameters are changed one at a time, while the rest stay at their Best Fit tuning.

Parameter	Best Fit (red)		Up (blue)		Down (green)	
	Simulink:	PSS/E:	Simulink:	PSS/E:	Simulink:	PSS/E:
Permanent droop, Rp, Norway	0,1	0,08	0,15	0,15	0,01	0,008
Permanent droop, Rp, Sweden	0,1	0,1	0,15	0,12	0,01	0,01
Transient droop, Rt	0,5	1,35	3	3	0,05	0,5
Governor time constant, Tr	4,3	2,6	6	6	2	2

6.5 Change of System Parameters H and D

More frequency dependent loads was found to reduce the amount of oscillations (see Chapter 3.3). In the Simulink model this can be simulated by increasing the damping constant, D, in the system block. More kinetic energy connected in the grid was found to reduce the oscillations as well. As inertia is proportional to rotational kinetic energy, this effect can be investigated by changing the H-constant. Simulations are run in Simulink with white noise input and zero deadband, for the three sets of values listed in Table 6.4.

Table 6.4: System parameter changes.

Parameter	H	D
Base Case	273,82	0
D $\neq$ 0	273,82	12
Reduced H	173,82	0

Chapter 7

Analysis of Parameter Changes

In this chapter the results of changing the governor parameters are presented. They are presented as time domain plots and power spectra, in order to identify both the amplitude and theperiodic time of the signals. In the last section of this chapter, the standard deviations of the simulated frequency responses are presented as a measure of variance.

The parameter change tests are performed in both the PSS/E model and in the Simulink model, but this chapter includes primarily the results from Simulink, for the sake of not making it too extensive. The Simulink simulations were chosen to be presented because the system parameters D and H can be changed more easily in the Simulink model, and due to the fact that deadbands can be implemented. Results from PSS/E indicating other effects than the Simulink tests will be pointed out. In the first two sections, 7.1 and 7.2, the Band-Limited White Noise block in Simulink is used as input to the load to create the random load changes and the undesired frequency variations. Later, when deadbands are added in Section 7.3, the time series object is used as input because the frequency amplitude it triggers then better resembles the real life variations.

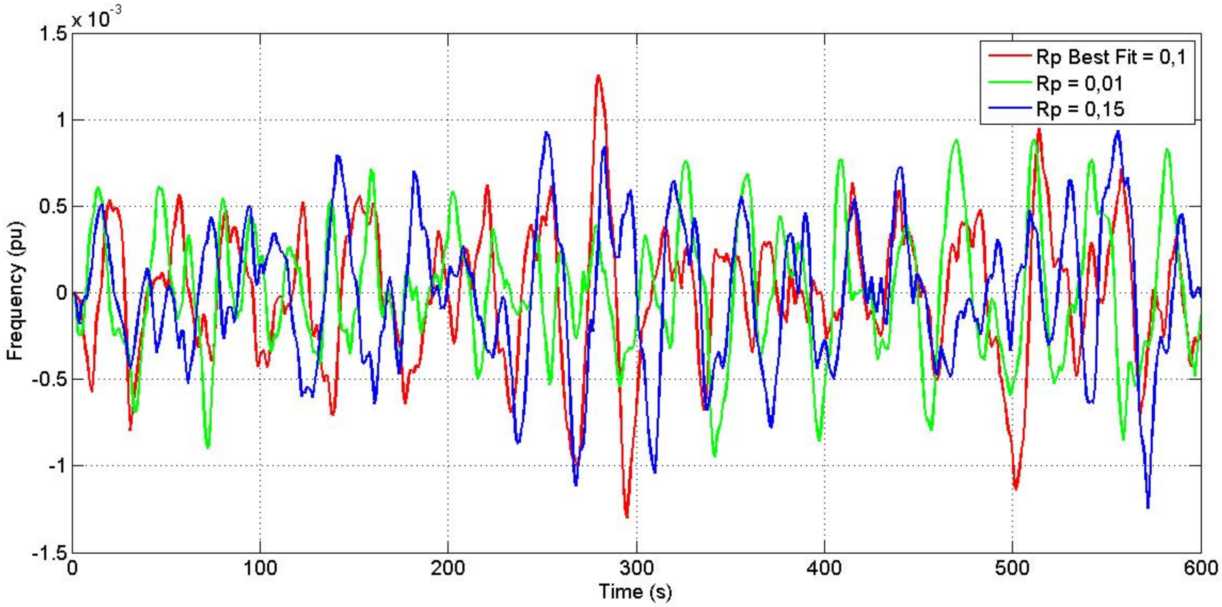

Figure 7.1: Frequency variations in Simulink, when subjected to load changes from the White Noise block (via a transfer function). R_p is changed, while the rest of the governor parameters are kept constant at their Best Fit values. $1 \cdot 10^{-3}$ pu = 50 mHz.

7.1 Time Domain

7.1.1 Changing R_p

In Figure 7.1 the permanent droop parameter has been increased and decreased, to see what can be achieved by tuning it right. From the time domain plot it is hard to see the difference in amplitude and periodic time for the frequency variations. There is a trend that the red and blue lines (corresponding to the highest parameter values) have a larger amount of small variations within the larger waves.

7.1.2 Changing R_t

Changing the temporary droop, R_t, results in a more visible change in the frequency oscillations, as can be seen in Figure 7.2. When increasing the temporary droop the system frequency is allowed to droop more during higher oscillation frequencies. This is because the proportional gain then gets smaller, and the controller behaves more like a pure integrator (see Figure 2.7). The fact that the frequency never reaches steady state (the load is changed continuously during

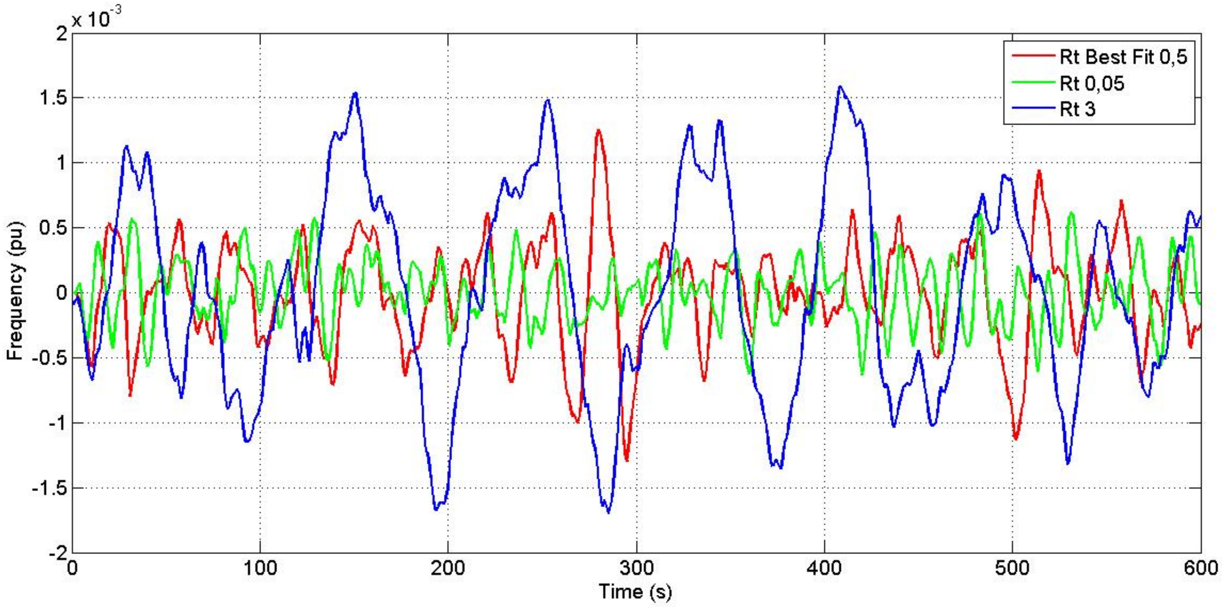

Figure 7.2: Frequency variations in Simulink, when subjected to load changes from the White Noise block (via a transfer function). R_t is changed while the rest of the governor parameters are kept constant at their Best Fit values. $1 \cdot 10^{-3}$ pu =5 0 mHz.

the simulation), can be an explanation for why the effect of changing R_t is more apparent than the effect of changing the permanent droop R_p (discussed in the previous section). However, the permanent droop also has an affect on how much the frequency droops during the transient stage.

Reducing R_t makes the frequency oscillate with a smaller period, and this will reduce the amount of oscillations. It should be noted that in a real life system, a too low R_t will have other effects that lead to instability. The PSS/E model, which is more advanced than the Simulink model, catches some of these effects. R_t had to be reduced from 1,35 to 0,5, instead of 0,05, because when the parameter was set too low it made the system unstable.

7.1.3 Changing T_r

The frequency variation in the Simulink model for different governor time constants, when subjected to white noise load changes, is plotted in Figure 7.3. Decreasing T_r from 4,3 to 2 results in a visible change in the frequency variations: the governor reacts more quickly and the average amplitude of the oscillations is larger. A high T_r will give a smaller amplitude, but a longer periodic time.

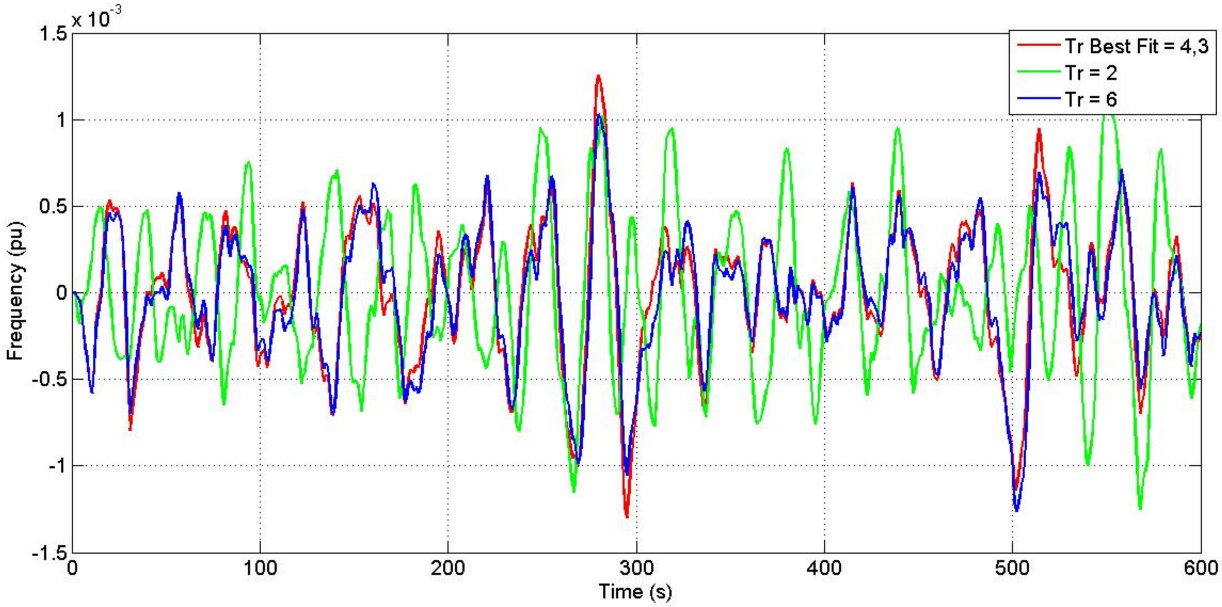

Figure 7.3: Frequency variations in Simulink, when subjected to load changes from the White Noise block (via a transfer function). T_r is changed while the rest of the governor parameters are kept constant at their Best Fit values. $1 \cdot 10^{-3}$ pu = 50 mHz.

7.2 Power Spectrum

In this section, the PSS/E results are plotted together with the Simulink results presented in the time domain section. The Matlab function pwelch(), which gives the Welch Power Spectral Density Estimate, is used to plot the spectra. Before the signals enter the function, they are filtered using the Matlab function filter(). The filtering and spectrum plotting process is described in Appendix B.5.

7.2.1 Changing R_p

Reducing R_p seems to have the effect that the periodic time of the frequency oscillations is reduced. The green lines in Figure 7.4 are both slightly shifted to the right. This corresponds to what could be noticed in the time domain plot in Figure 7.1: that the red and blue lines have a larger amount of small variations within their larger wave forms. Permanent droops of 0,01 and 0,15 are already outside the limits of the realistic parameter values listed in Chapter 2.5. To see a shift towards the left, R_p has to be increased even more than from 0,1 to 0,15. However, it is interesting to notice that for low frequencies (high periodic times), the signal with the lowest permanent droop contains the most power, whereas for high frequencies it is opposite: the lowest permanent droop contains the most power.

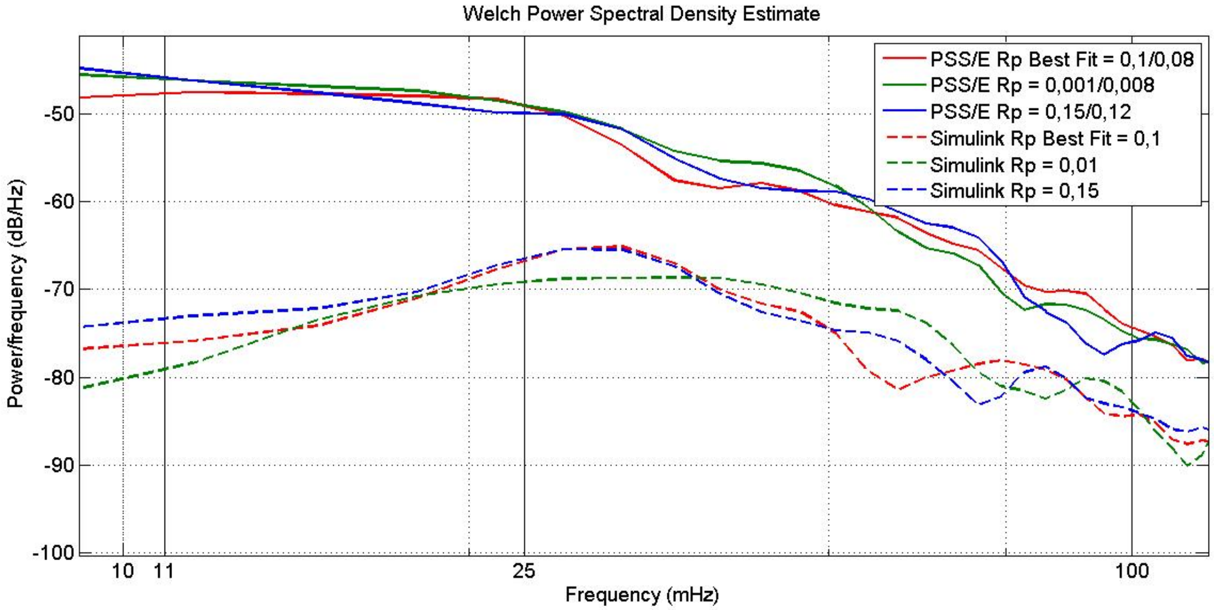

Figure 7.4: Power spectra of frequency variations from both the PSS/E model the Simulink model (the same as were plotted in the previous section), when subjected to random load changes generated by the White Noise block in Simulink, and by the Python script in Appendix B.6 in the PSS/E model. R_p is changed while the rest of the governor parameters are kept constant at their Best Fit values. The frequency at which the plot peaks, corresponds to the most apparent periodic time of the frequency signal.

7.2.2 Changing R_t

A tuning with a low transient droop, R_t, allows the frequency to drop less while the system frequency oscillates with higher frequencies. From Figure 7.5 it can be seen that a big transient droop results in a lower frequency on the frequency variations. This corresponds to the time domain plot discussed in section 7.1.2. When the droop is large, the governor needs more time to restore the frequency, and so the variations are slower. Here, there is a significant difference in the results from Simulink simulations and PSS/E simulations: the case in which the parameter is increased seems to give a much lower oscillation frequency in the Simulink model than in the PSS/E model. Simulations from both models indicate that a reduced R_t gives a less low-frequent oscillation. The fact that a too low R_t will make a power system unstable is reflected in the PSD plot: for the simulation with a unrealistic low R_t in Simulink, the power is high for high frequencies. Remember that the PSS/E model would not run with such a low setting.

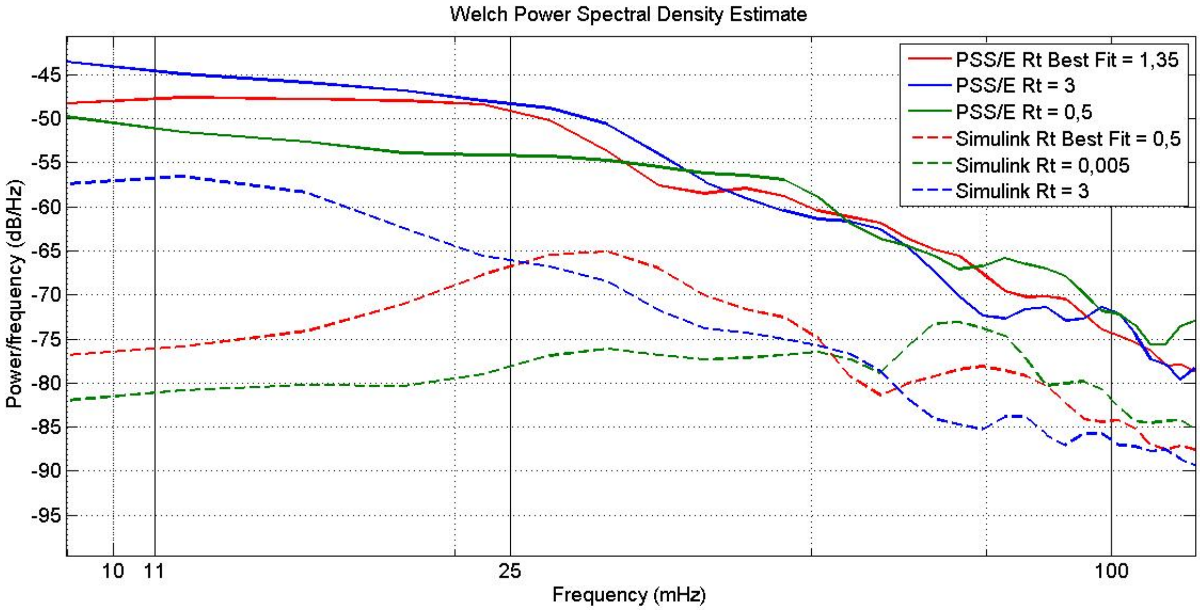

Figure 7.5: Power spectra of frequency variations from both the PSS/E model the Simulink model (the same as were plotted in the previous section), when subjected to random load changes generated by the White Noise block in Simulink, and by the Python script in Appendix B.6 in the PSS/E model. R_t is changed while the rest of the governor parameters are kept constant at their Best Fit values. The frequency at which the plot peaks, corresponds to the most apparent periodic time of the frequency signal.

7.2.3 Changing T_r

When the governor time constant, T_r, is reduced, the governor responds faster. The periodic time of the frequency variations is therefore reduced, and the most apparent oscillation frequency in Figure 7.6 is higher for the simulation where T_r was reduced. The peaks of the green lines are further to the right than the peaks of the lines that belong to the two cases with longer time constants, which indicates that a long time constant causes more low-frequent oscilla-

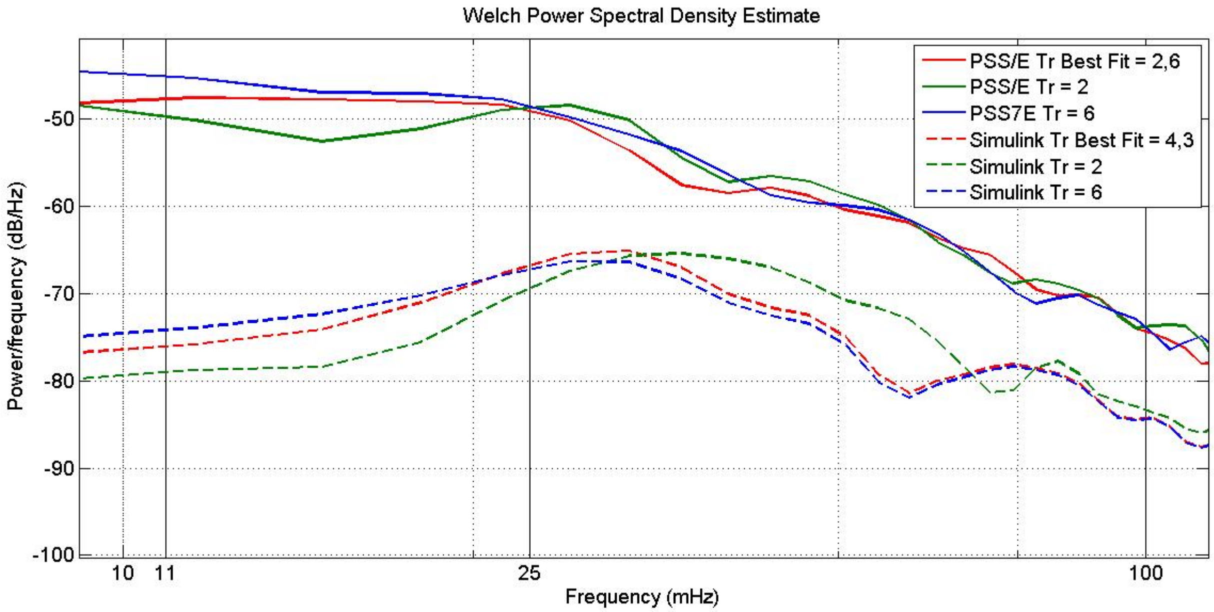

Figure 7.6: Power spectra of frequency variations from both the PSS/E model the Simulink model (the same as were plotted in the previous section), when subjected to random load changes generated by the White Noise block in Simulink, and by the Python script in Appendix B.6 in the PSS/E model. T_r is changed while the rest of the governor parameters are kept constant at their Best Fit values. The frequency at which the plot peaks, corresponds to the most apparent periodic time of the frequency signal.

tions. The signal with a high time constant contains the most power for low frequencies, for higher frequencies it is completely opposite.

7.3 Deadband

As the PSS/E model does not have deadbands implemented on the generators, the results in this section are from simulations in Simulink only. The functionality of the deadband is illustrated in Figure 7.7 and in Figure 7.8. The regulators stay inactive until the frequency deviation is outside the deadband.

Figure 7.8 demonstrate that the permanent frequency droop after the load step change is dependent on the deadband size, not only on the permanent droop parameter, R_p, which is kept constant. The response the set of load changes saved in the time series object now produce has a larger amplitude. This makes the response more similar to the PMU measured variations

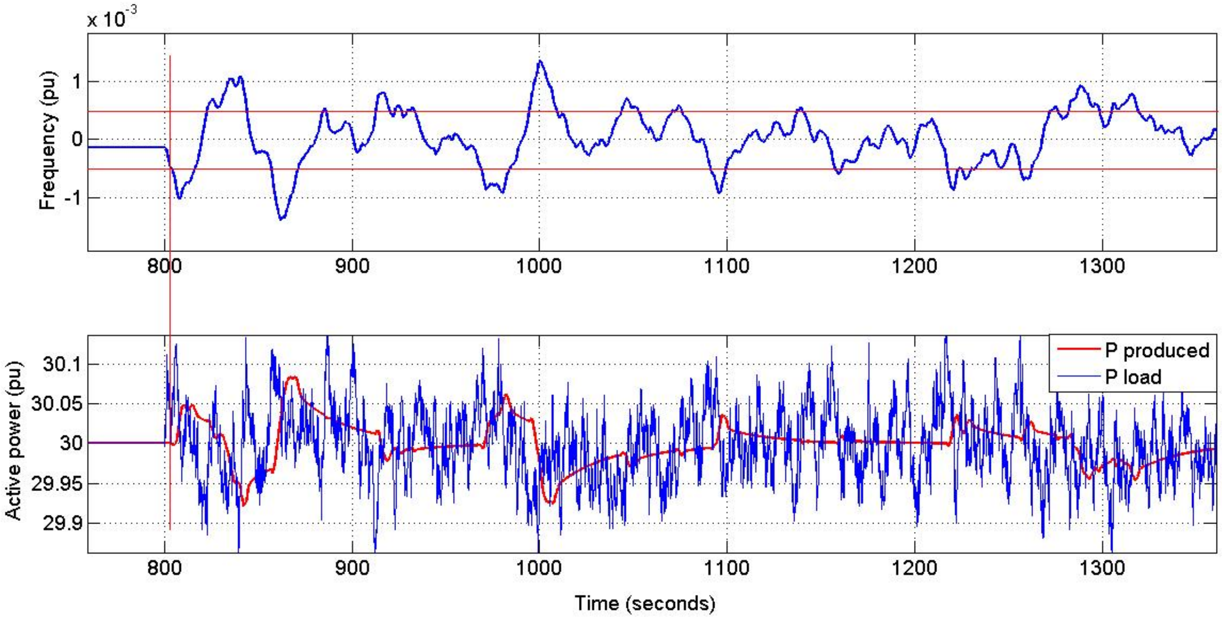

Figure 7.7: A deadband of 0,0005 pu (0,025 Hz) on all the generator governors in Simulink. Load changes generated by the White Noise block (via transfer function) are added to the constant system load of 30 pu (30 000 MW) to create a random changing load (blue line). The power output from the governors (red line) is not changed until the frequency deviation is outside the deadband. The point where the governors start to take action is indicated by the vertical red line. Horizontal red lines in the top plot mark the deadband.

than previously when the simulations were run without deadbands. In Figure 6.5 the simulated frequency variations, with and without deadband, are plotted. The response of the white noise load change, which without deadband was the one that resembled the PMU variations the most, is now less similar because the amplitude is amplified by the deadband.

The power spectra of simulations with and without a deadband in Figure 7.9 reveals that the oscillation period is larger when there are deadbands on the generators. Without deadband the power spectrum displays a periodic time of about 30 s, with a deadband it is shifted to about 50 s.

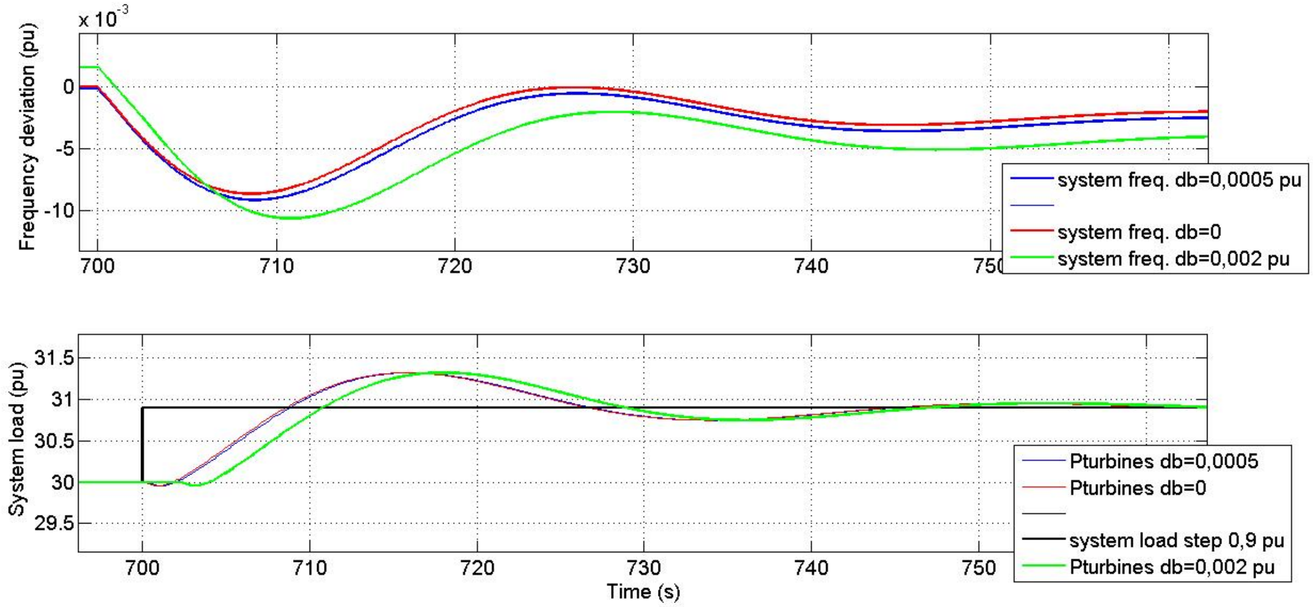

Figure 7.8: Different sized deadbands are implemented on all the generators. A step change in the load of 0,9 pu (900 MW) is applied at t = 700 s. R_p is kept constant. In the top: frequency deviation in pu following the step change. Bottom plot: system loading with step (pu), together with power supplied by the turbines. Red lines: no deadband. Blue lines: deadband of 0,0005 pu (0,025 Hz). Green lines: deadband of 0,002 pu (0,1 Hz).

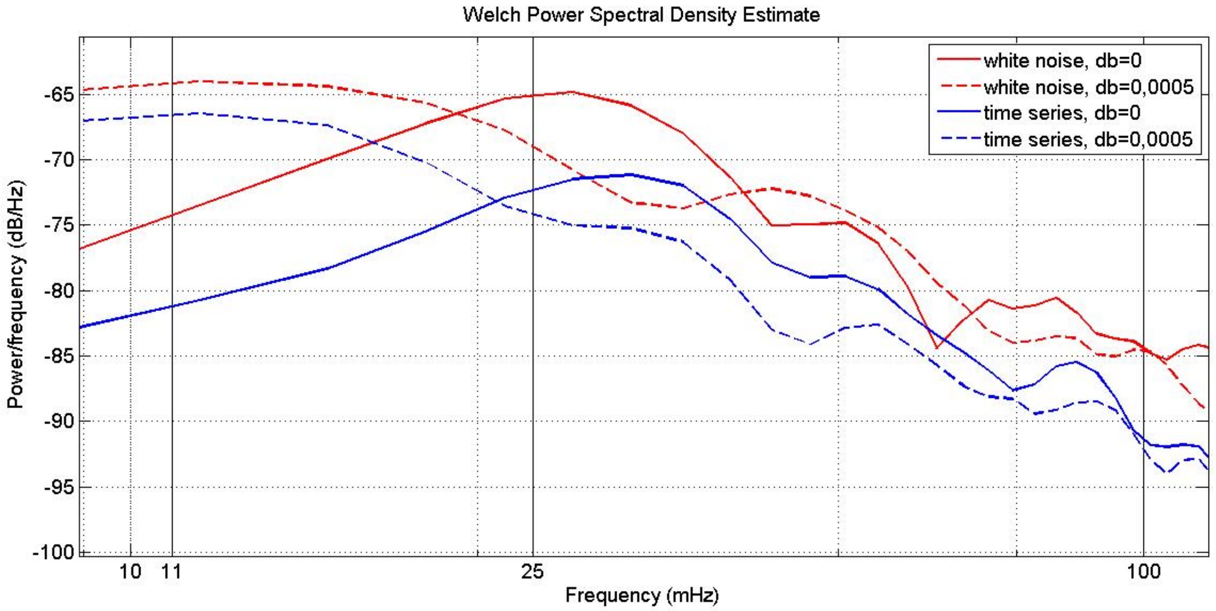

Figure 7.9: Power spectrum of Simulink frequency variations: time series and White Noise block (via a transfer function) load changes, with and without a deadband of 0,0005 pu (0,025 Hz).

7.4 Changing System Parameters D and H

In 7.10 the power spectra of simulations run in Simulink with the different system parameter values of Table 6.4 are plotted. Increasing D reduces the periodic time of the variations. Reducing H has the same effect. A reduced periodic time reduces the amount of oscillation. It was expected that less inertia in the system (reduced H) would make the oscillations less slow.

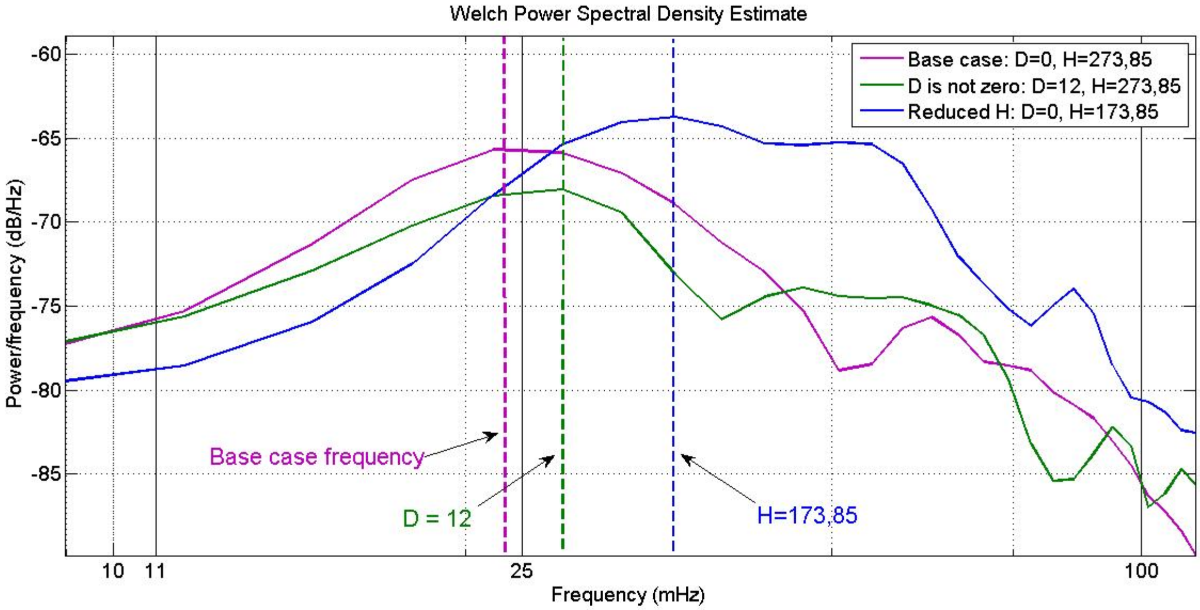

Figure 7.10: Power spectrum of frequency response in Simulink, with White Noise block (via a transfer function) load changes. Simulations are run with different sets of system parameter values, see Table 6.4.

7.5 Standard Deviation of the Frequency Variations

Summing up this chapter of results, the standard deviation of the respective simulations performed is presented. As mentioned already in the introduction in Chapter 1, the variance of the system frequency in the Nordic grid has increased over the last years. This aspect of the oscillations is important in addition to the periodic time, when addressing the problem of frequency oscillations. A large variation, or dispersion from the average, in the frequency means it is outside the Grid Code decided limits more often. If the periodic time is large at the same time, the frequency stays outside the limits for a longer period and the problem gets more severe.

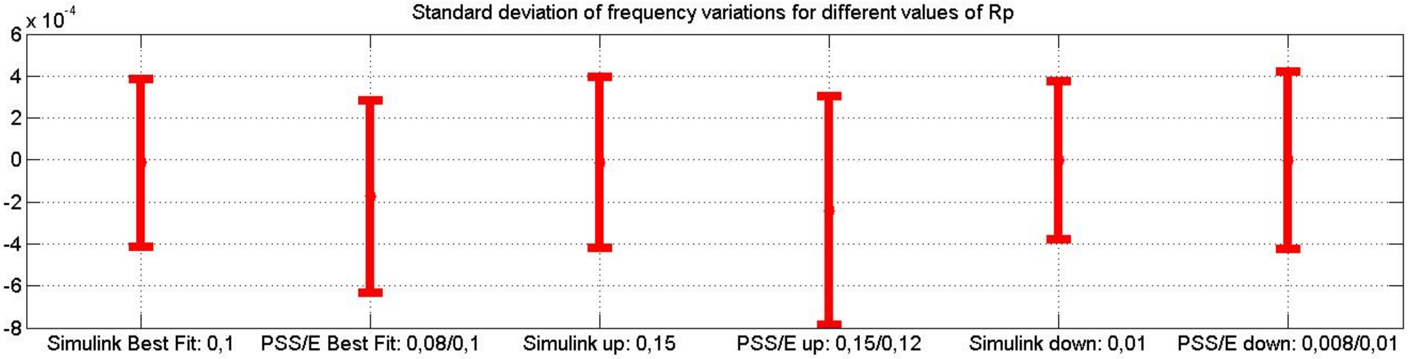

Figure 7.11: Standard deviation of simulations run in Simulink with different permanent droops. Load changes from the White Noise block via a transfer function. The signals (all in pu) are the same that were plotted in Section 7.1.1. The midpoints of the bars are the average values of the signals.

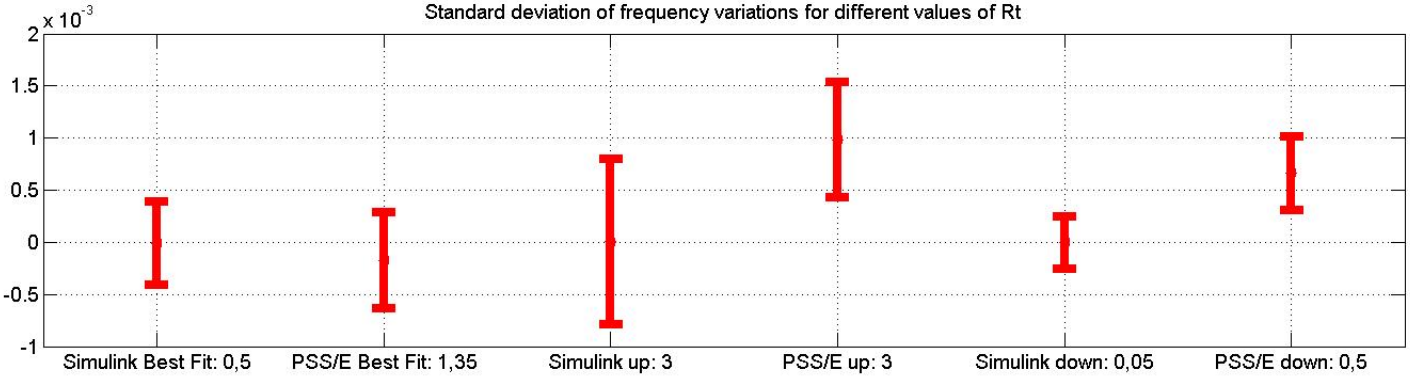

Figure 7.12: Standard deviation of simulations run in Simulink with different transient droops. Load changes from the White Noise block via a transfer function. The signals (all in pu) are the same that were plotted in Section 7.1.2. The midpoints of the bars are the average values of the signals.

The standard deviation is a measure of variance, as it is the square root of the variance of the signal. Figures 7.11, 7.12 and 7.13 present the standard deviations of the simulated pu frequency with changed governor parameters (following Table 6.3). It can be seen that the variance is generally higher for the PSS/E simulations, than for the simulations run in Simulink. Simulations from both models indicate that R_p should be reduced in order to decrease the variance of the frequency variations. However, the change in Simulink standard deviation is minimal and hardly visible.

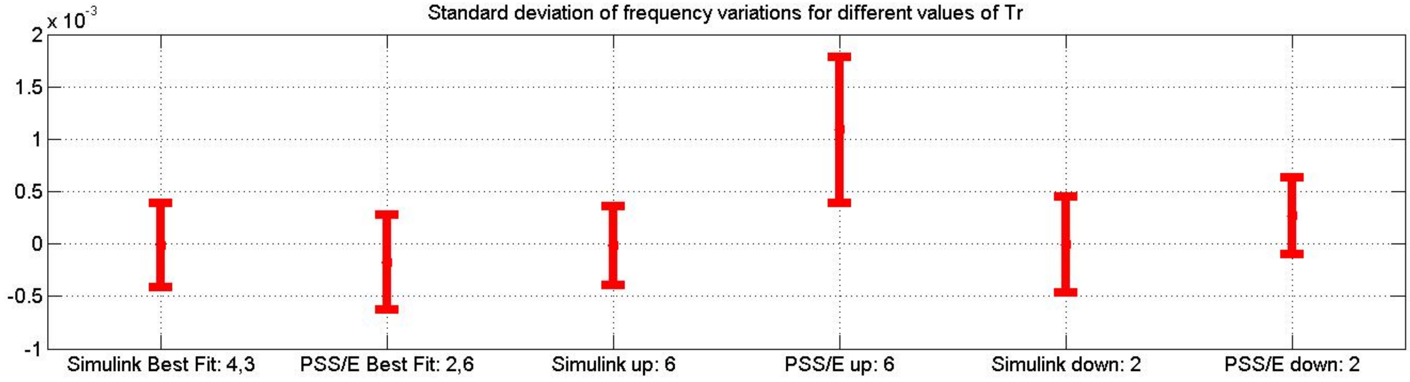

Figure 7.13: Standard deviation of simulations run in Simulink with different governor time constants. Load changes from the White Noise block via a transfer function. The signals (all in pu) are the same that were plotted in Section 7.1.3. The midpoints of the bars are the average values of the signals.

Increasing R_t results in a larger variance. It is hard to draw a conclusion from the governor time constant results, because they point in different directions. The Simulink results indicate that an increased T_r will decrease the variance, whereas PSS/E results indicate the opposite effect. In Chapter 3.3 it is described how the time constant has a larger impact on the periodic time than on the amplitude of the frequency oscillations. This could be an explanation as for why the changes in variance do not point in the same direction.

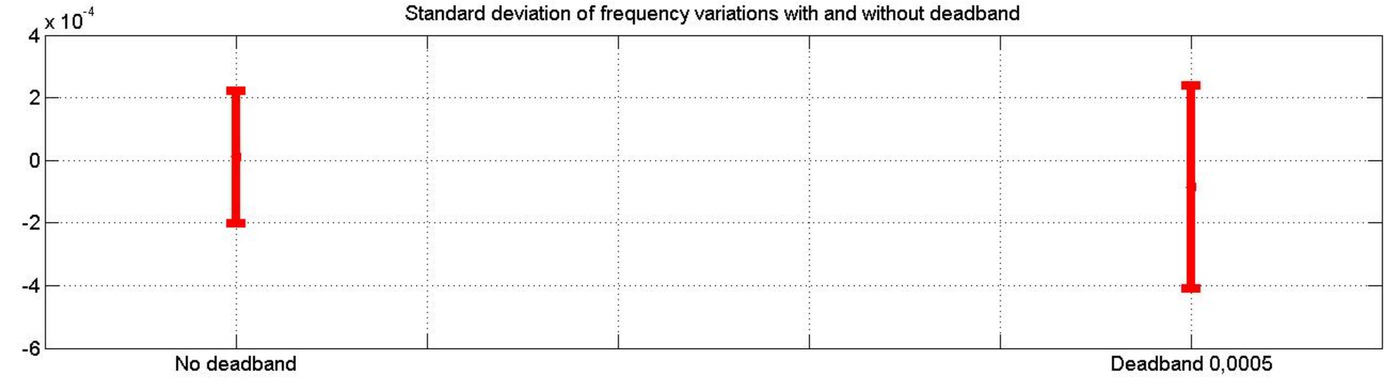

Figure 7.14: Standard deviation of simulated frequency variation in pu, simulated in the Simulink model, with and without a deadband of 0,0005 (0,025 Hz). Time series load changes. The midpoints of the bars are the average values of the signals.

When investigating the effect of deadbands, the time series object was used as load disturbance in the Simulink model. Examining Figure 7.14, the first thing to notice is that the standard deviation with no deadbands is only half of what it is for the simulation with deadbands on the generators. The effect of introducing deadbands on all governors is quite clear: the deadbands make the variance increase.

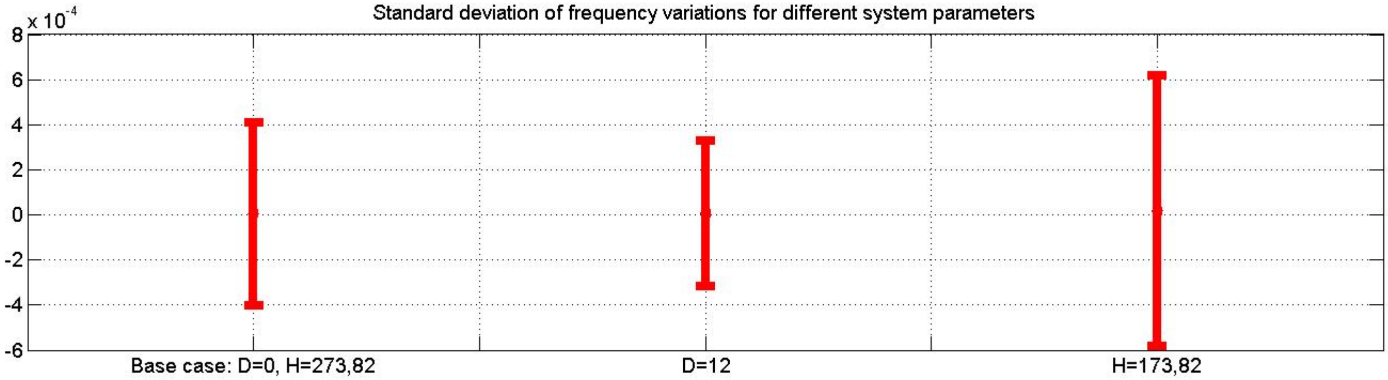

Figure 7.15: Standard deviation of simulated frequency variations in pu, simulated in the Simulink model, with different system parameters listed in Table 6.4. White Noise block (via a transfer function) load changes. No deadband. When one variable is changed, the rest keep the Base case value. The midpoints of the bars are the average values of the signals.

The standard deviations in Figure 7.15 indicate the expected effect of changing the damping and inertia in the system. When D is increased, there is less variance, and reducing the inertia constant H results in a larger frequency variance. Although the power spectrum plot discussed in Section 7.4 shows that the periodic time reduces when H is reduced, the variance is increased, and so the amount of oscillations may still increase with reduced H.

Chapter 8

Summary and Conclusions

8.1 Summary and Conclusions

A simple Simulink model has been developed based on Sintef's PSS/E 23 generator model of the Nordic grid. Both models have been used to meet objective 1 of this Thesis: to simulate the slow frequency oscillations in the Nordic power grid. The hydro governors were tuned so that a 900 MW loss of production resulted in a frequency response similar to a real life event in Sweden 11.06.2011. The modeled systems were subjected to load changes that made their frequency responses resemble PMU recorded frequency variations. If the time interval between the load changes is increased, the amplitude of the frequency oscillations go down. Changing the load in smaller steps will also reduce the amount of oscillations. The TSO work group behind [1] found the amount of oscillations to be largest around the hour shifts, which is associated with load adjustments in the system. None of the load changing schemes are successful when it comes to creating frequency variations exactly like the ones observed in the grid.

Similar changes in the frequency responses were found in both the PSS/E model and the Simulink model when the respective governor parameters were changed, and random load changes were applied to the system. Tuning the governor parameters has an effect on the frequency oscillations. Reducing the governor time constant, T_r, will make the frequency oscillate with a longer period. A large transient droop, R_t, allows the frequency to drop lower before steady state is regained. This results in slower variations, and the oscillations are more low-frequent. Reducing R_p, the permanent droop, seems to increase the oscillation frequency. To make the periodic time of the oscillations smaller, and by that reduce the amount of oscillation, T_r should be increased, while R_p and R_t should be reduced. This answers objective number 2 listed in the introduction chapter.

A dead band was implemented in the Simulink governor model, as this can cause oscillations and destabilize a system with unfortunate damping and inertia values. Deadbands were found to increase both the amplitude and the periodic time of the frequency oscillations.

While searching for a suitable tuning of the models, and load changing scheme, it was discovered that the inertia constant, H, and the damping constant, D, have a great impact on the oscillatory characteristics of the frequency variations. As this was factors the TSO work group found to contribute to frequency oscillations, their impact was investigated further in Chapter 7.4. Increasing D made the periodic smaller, and reducing H was found to have the same effect on the periodic time. When studying the standard deviation, as a measure of variance in the signal, reducing H was found to increase the variance. All in all, the amount of oscillation seems to be increasing for a lower inertia constant. This confirms that there are other parameters than the hydro governor parameters that contribute to the slow frequency oscillations, and partly answers objective number 3.

One week of PMU measurements studied in Chapter 4 did not indicate the same differences between day and night time that the TSO work group found.

8.2 Discussion

In the process of finding a suiting load change scheme it became clear that the way the load is changed affects the frequency oscillations. If the time between the load changes increases, the amplitude of the oscillations decreases. Likewise, the amplitude will decrease if the load changes are made smaller. This is true also in the PMU studies done by the TSO work group in [1], which states that the amount of oscillation increases when hour shifts occur. Neither of the load changing schemes are perfect, the period of the oscillations is too small for all of them, compared with the one observed in the Nordic system. But as the governor parameters' effect on the variations is the same for the PSS/E model and the Simulink model, which have been run with different load changing schemes, it will probably be the same for oscillations with the right periodic time. It is reasonable to believe that the results still are relevant.

With randomly generated load changes, the frequency variations will be random. The system parameters make the frequency swing in a certain way given a certain load change, and a bigger change in load will affect the frequency more than a small one. The simulations performed in this work should have been executed an even greater number of times to say with certainty what the effects of the parameter changes are. It should be pointed out that the simulations have been run more times than what the results presented in the report indicate. For most of the simulations, the effects of the parameter changes are the same in both models, and the results are consistent with the theory on the subject. This strengthens the validity of the results. If the work presented in this Master Thesis was to be continued, a more quantitative analysis of the parameters' effect on amount of oscillation should be performed. This would give a better basis for comparing the different parameters' effect on the frequency variations.

The effects of changing governor and system parameters were mostly as expected based on theory and findings by the TSO work group. Deadbands were found to increase the amount of oscillation, both in terms of periodic time and variance. Like the work group stated in [1], the amount of oscillation is reduced when the transient droop parameter, R_t, is reduced. Increased proportional part ($K_p = \frac{1}{R_t}$) of the controller reduces both the periodic time and the variance. The change of system inertia was the only parameter that did not cause the periodic time and variance to change in the same direction.

A change of parameter settings in the real life grid will take a long time to execute, and will be costly for the producers [1]. Therefore more investigation needs to be done on the subject, to make sure the parameters are set right, and that the change will not have other negative effects on the power system.

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Appendix A

Symbols and Abbreviations

A.1 Symbols

δ Voltage angle [rad]

δ_m Rotor angle [rad]

λ Eigenvalue

ω Rotational speed = $2\pi f$ [rad/s]

ω_m Rotor shaft speed [rad/s]

ω_{synch} Synchronous speed [rad/s]

ω_i Imaginary part of eigenvalue λ_i

τ_e Electromagnetic torque [Nm]

τ_{mech} Net mechanical shaft torque [Nm]

τ_t Turbine torque [Nm]

σ_i Real part of eigenvalue λ_i

v Eigenvector

$\mathbf{x}$ State vector

$\mathbf{A}$ State matrix

f Frequency [Hz]

f_n Nominal frequency (50 Hz in the Nordic power system)

D System damping constant

D_d Damping torque coefficient [Nms]

G Gate opening

H Inertia constant [s]: stored kinetic energy at synchronous speed, divided by the machine rating

J System inertia constant [kg m^2]

K Governor gain

K_T Frequency sensitivity coefficient of the power production [MW/Hz]

K_L Frequency sensitivity coefficient of the power demand [MW/HZ]

K_f System stiffness ($K_T + K_L$) [MW/Hz]

M_{base} Base value for pu conversion [MVA]

N_G Number of generating units

P Active power [W]

P_L Active power loading [W]

P_n Nominal active power production [W]

ΔP_T Toatal change in active power production

$P_{turbine}$ Active power production [W]

Q Reactive power [VAr]

R_p Permanent droop

R_t Transient droop

s Laplace operator $\frac{d}{dt}$

T Periodic time (period) T=1/f [s]

T_{el} Electrical torque [Nm]

T_f Filter time constant [s]

T_g Servo time constant [s]

T_i Integrating time constant [s]

T_{mec} Mechanical torque [Nm] produced by the turbine

T_r Governor time constant [s]

T_w Water time constant [s]

U Step input

A.2 Abbreviations

AGC Automatic Generation Control

db deadband

ENTSOE-E European Network of Transmission System Operators for Electricity

FCR Frequency Containment Reserves

FNR Frequency controlled normal reserve. Activated for frequency deviations within ±0,1 Hz.

FDR Frequency controlled disturbance reserve. Activated for frequencies outside the range of ± 0,1 Hz.

FRR Frequency Restoration Reserves

PID Proportional-Integral-Derivative (controller)

PMU Phasor Measurement Unit

PSD Power Spectral Density

pu per unit

RR Replacement Reserves

TSO Transmission System Operator

Appendix B

Additional Information

B.1 Model Description Simulink

Machine data copied from the PSS/E model are given in Table B.2.

The system is represented by the block given by Equation 5.1, and the system parameters are listed in B.1.

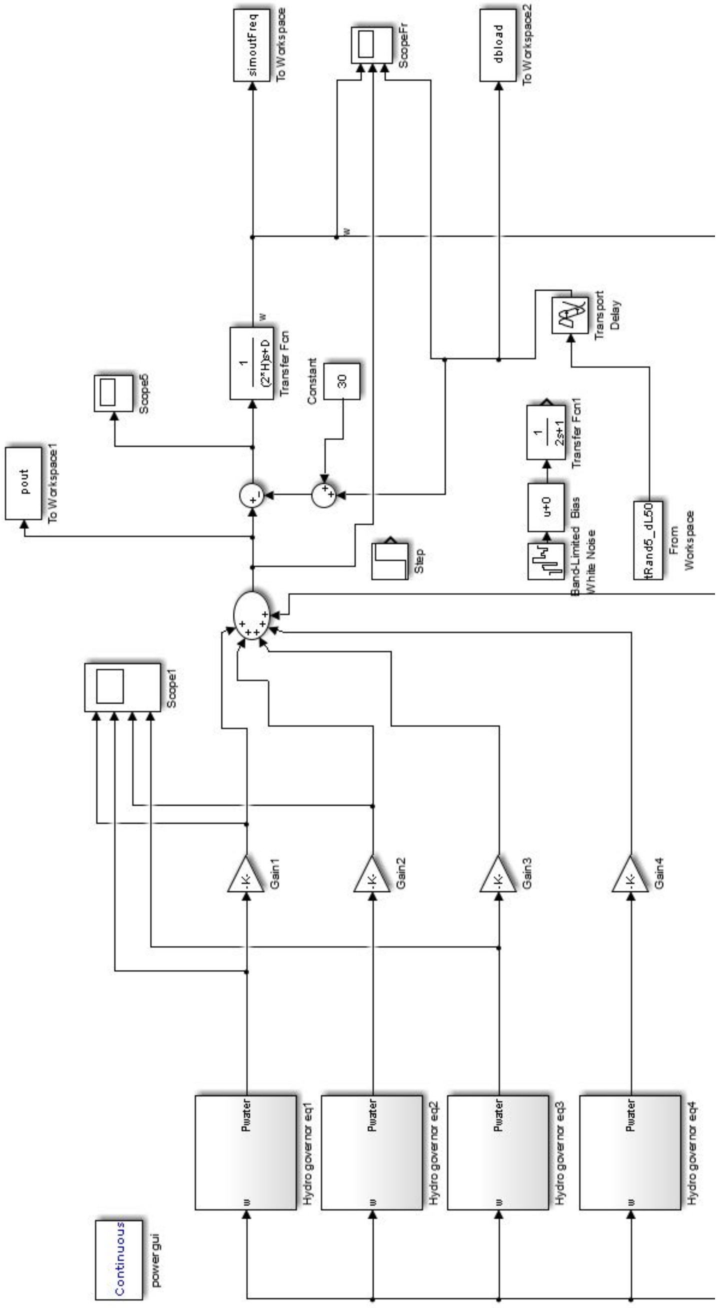
Table B.1: System parameters.

Parameter	
H	273,82 s
D	0
ω_{ref}	0
P_{load}	30 pu
S_{base}	1000 MVA

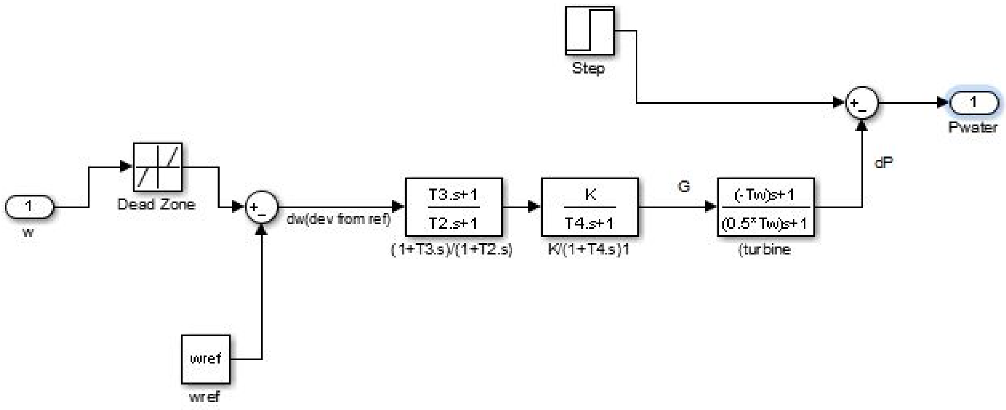
Table B.2: Generator parameters. The ones marked $*$ are not hydro generators, and were not implemented in the Simulink model.

Generator Number	Mbase [MVA]	H [s]
$*$	6500	5,96
1	2500	5,04
2	4000	4,7410
3	1500	3,3
4	5500	4,543
$*$	5000	6
5	4100	3,3
$*$	900	4,82
6	1800	3,9871
7	2750	3,5
8	1900	4,1
9	1000	3
10	2850	3,5
11	1400	3,5
12	2900	3
13	1900	3,558
14	3400	3,5920
$*$	6500	5,5
15	1800	3,2
$*$	2000	7

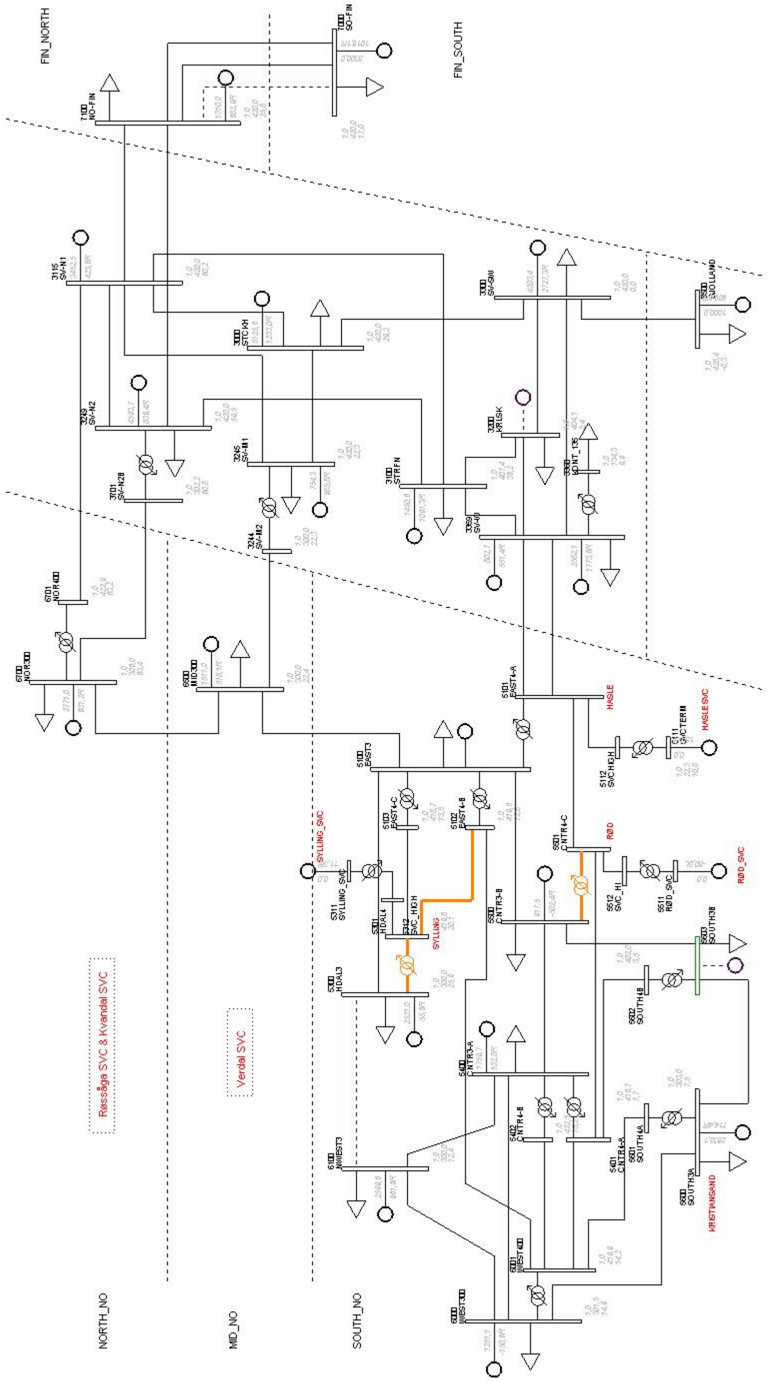
B.2 Segment of Simulink Model



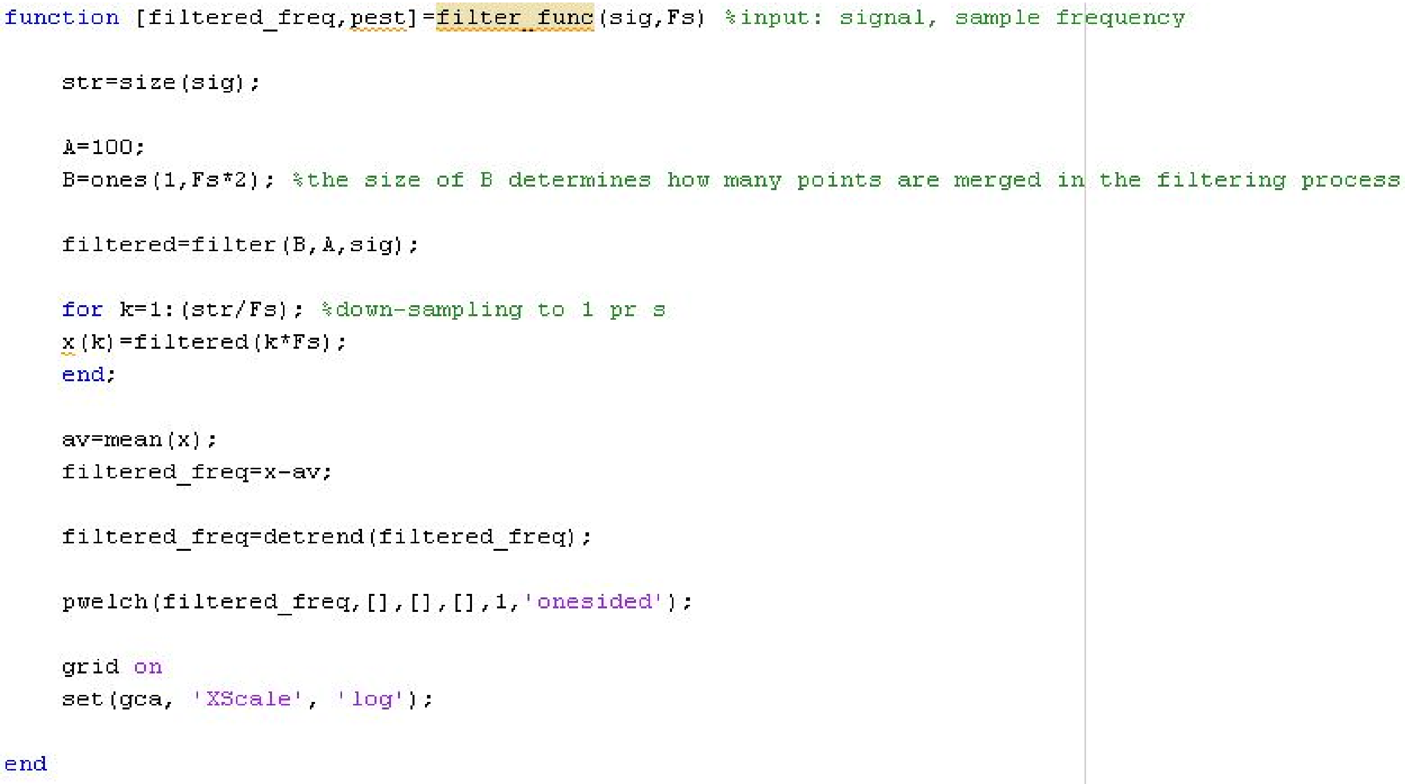
B.3 Governor Simulink Model



B.4 One Line Diagram PSS/E Model



B.5 Filtering function



```
function [filtered_freq,pest]=filter_func(sig,Fs) %input: signal, sample frequency

    str=size(sig);

    A=100;
    B=ones(1,Fs*2); %the size of B determines how many points are merged in the filtering process

    filtered=filter(B,A,sig);

    for k=1:(str/Fs); %down-sampling to 1 pr s
    x(k)=filtered(k*Fs);
    end;

    av=mean(x);
    filtered_freq=x-av;

    filtered_freq=detrend(filtered_freq);

    pwelch(filtered_freq,[],[],[],1,'onesided');

    grid on
    set(gca, 'XScale', 'log');

end
```

B.6 Load Change Python Script

```
deltaT=5

t=float(random.randrange(1,deltaT))

load1=5610
load2=2700
load3=2526
load4=1854
load5=1825
load6=3360

while t< 600:
    psspy.run(0, t,1,1,0)
    bus= int(random.choice(buses))
    load_change=float(random.randrange((-deltaL),deltaL))

    if (bus==3300):
        mbase=5000
        load1=load1+load_change
        load=load1
    elif (bus==3359):
        mbase=4100
        load2=load2+load_change
        load=load2
    elif (bus==5100):
        mbase=1800
        load3=load3+load_change
        load=load3
    elif (bus==5600):
        mbase=2850
        load4=load4+load_change
        load=load4
```

```
        elif (bus==6100):
                mbase=2900
                load5=load5+load_change
                load=load5
        else:
                mbase=6500
                load6=load6+load_change
                load=load6
        psspy.load_chng_4(bus,r"""1""",[_i,_i,_i,_i,_i,_i],[_f,_f, load ,_f,_f,_f])
        t=t+float(random.randrange(1,deltaT))


psspy.run(0, 620.0,1,1,0)


pssplot.newplotbook()
pssplot.insertpage()
pssplot.setselectedpage(0)
pssplot.insertplot()


pssplot.setselectedplot(0)
pssplot.openchandatafile(r"""M:\Mstr\load_changeN.out""")
pssplot.dragdropplotdata(r"""load_changeN""",r"""1 - FREQ   5101 [EAST4-A
420.00]""")


pssplot.setselectedplot(1)
pssplot.dragdropplotdata(r"""load_changeN""",r"""2 - PLOD  3300[SV-SW
420.00]1""")
pssplot.dragdropplotdata(r"""load_changeN""",r"""3 - PLOD  3359[SV-W
420.00]1""")
pssplot.dragdropplotdata(r"""load_changeN""",r"""4 - PLOD  5100[EAST3
300.00]1""")
pssplot.dragdropplotdata(r"""load_changeN""",r"""5 - PLOD  5600[SOUTH3A
300.00]1""")
pssplot.dragdropplotdata(r"""load_changeN""",r"""6 - PLOD  6100[NWEST3
300.00]1""")
pssplot.dragdropplotdata(r"""load_changeN""",r"""7 - PLOD  7000[SO-FIN
420.00]1""")
```