CODEN:LUTEDX/(TEIE-5201)/1-76/(2005)

Industrial Electrical Engineering and Automation

Damping in the Icelandic power system

Small signal stability analysis and solutions

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Abstract

Sufficient damping of oscillations is important in an interconnected power system. This thesis addresses the topic of such damping in the Icelandic power system, after increase in its capacity. The Icelandic power system is based on a strong 220 kV network connected to a weak ring network of 132 kV. Therefore there is a risk of unbounded oscillations arising after faults. Such oscillations are a matter of small signal stability. The purpose of this thesis is to apply modal analysis to a linearized model derived from a standard nonlinear model. By applying modal analysis, oscillation modes in need of increased damping can be identified. Based on such an analysis, a damping strategy, based on power system stabilizers, can be devised. The design of such a strategy is described and results of time simulations with the strategy implemented. The results of tuning and installing power system stabilizers at strategic locations are that damping can be improved significantly in the system.

Acknowledgments

This thesis has been based on data from the Icelandic transmission operator, Landsnet. I would like to place special thanks to Landsnet for letting me use their data. During the work on this thesis I also received a stipend from the Icelandic power company, Landsvirkjun. To Landsvirkjun I express my gratitude.

My supervisor under this work has been Prof. Olof Samuelsson. I am very grateful for his guidance in this work. He has taught me a lot about power systems, as well as helped me make it possible to get the data. In this work I have also received guidance from Chavdar Ivanov whom I would like to thank for many interesting discussions about power system stabilizers and a lot of help on how to manage their tuning. I would also like to thank Sture Lindahl and Morten Hemmingsson for help and enlightening talks about power systems.

Finally I would like to thank my spouse, Elva Rakel, and our daughter Freydís Edda. Without your love and cheerful smiles in the morning this would have been much harder.

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Glossary

Abbreviations

AVR	Automatic Voltage Regulator
PSS	Power System Stabilizer
FACTS	Flexible AC Transmission Systems
SVC	Static Var Compensator
HVDC	High Voltage DC Link
SSS	Small Signal Stability
DAE	Differential Algebraic Equation
ODE	Ordinary Differential Equation

Variables

$\Delta\omega$	Generator rotor speed
$\Delta\delta$	Generator rotor angle
T_e	Electrical torque
T_m	Mechanical torque
P_e	Electric power
P_m	Mechanical power
K_S	Synchronizing torque coefficient
K_D	Damping torque coefficient
V_{ref}	AVR voltage reference signal
V_t	Generator terminal voltage

Chapter 1

Introduction

1.1 History

In the earlier days of electricity generation, power systems consisted mainly of single power plants connected by transmission lines to a single load center. The lack of synchronizing torque in these systems soon caused instability problems as load increased. Interconnection of such systems was early seen to be efficient as it would strengthen the system, improve stability and meet increasing demand. With the increased load of these systems, more complex instability problems arose such as low frequency oscillations due to faults.

The first measure that was taken in order to damp oscillations was to add damper windings (amortisseurs) to the rotors of generators in order to introduce damping to rotor speed oscillations. This provided a solution to the oscillation problem for a while until the systems grew in size even more and oscillation problems reoccurred.

The introduction of automatic voltage regulators (AVR) improved stability of the power system significantly by increasing synchronizing torque. However since they were first commissioned it has been noted that they can have detrimental effect on damping. This has been known to lead to low frequency oscillations local to plants and their close surrounding area.

Increased interconnection of power systems has lead to a structure of close generator groups connected to other groups by weak transmission lines. This has been known to cause oscillations were these groups oscillate against each other in an inter area fashion. This implies that power oscillates between areas and thus diminishes the transmission capability of the interconnected system.

Growing oscillations eventually lead to loss of synchronism in a power system which can cause damage. In order to prevent damage under such circumstances, generators would have be disconnected from the system. This can cause disturbances or even worse, blackouts. Damping of oscillations thus plays a significant role in power system security by securing and increasing supply and transmission capability of the system [1], [2].

1.2 Solutions

The solution to the oscillation problem in power systems has been to try to add a damping component to the electrical torque (T_e). This has been done by modulating the control signal of the AVR (V_{ref}) by feedback through a so called power system stabilizer (PSS). The PSS is tuned so that it provides damping over a wide range of frequencies in order to damp as many oscillations as possible.

Other options to dampen low frequency oscillations in power system are for example through control of flexible AC transmission system (FACTS), e.g. static var compensators (SVC), and high voltage DC links (HVDC). The use of PSS is although the most widespread strategy used today [1].

1.3 Goals

The Icelandic power system is experiencing structural changes at the time this thesis is written. The installed capacity of the system is approximately 1500 MW and is being increased in three locations. The most impact on the structure of the system has a hydro power plant of 690 MW in the eastern part of Iceland at Kárahnjúkar. This power plant will be connected to a 132 kV ring network with other relatively large hydro power plants. The ring is connected to a strong network of 220 kV with large generation capacity in the south.

These structural changes of the system are likely to alter the characteristics and behavior of the system. This is because of the location of the power plant in a otherwise weak network. A mechanical analogue to this would be masses connected by springs. In this case the 132 kV transmission lines would be the equivalent to lightly damped springs and the 220 kV transmission lines would be the equivalent to stiff springs. This means that the 220 kV system in the south would move approximately as one mass connected by lightly damped springs to the power plants on the ring network. A disturbance in this system would cause the system to vibrate/oscillate. The new power plant would be an equivalent to a very big mass compared to the other power plants on the ring network and therefore it is very interesting to learn how the new system will behave.

The goal of this thesis is to analyze the power system after the increased capacity has been installed. Analyzing oscillations is done by applying small signal stability (SSS) analysis. SSS analysis implies linearizing the power system model around a stable operating point and applying eigenanalysis to the result. In this way the oscillating behavior of the system can be analyzed for disturbances close to the operating point. On the grounds of this analysis of the system it is possible to determine where damping should be applied in order to damp all possible oscillations sufficiently. This is done by using a PSS. The second goal is therefore to design a damping strategy for the modified system.

Chapter 2

The Icelandic power system

The goals of this thesis are to analyze the behavior of the Icelandic power system after increase in its capacity. It is therefore appropriate to introduce some information about the current system in order to serve as a background to this thesis.

2.1 Capacity and generation

According to the cooperation of transmission system operators in the Nordic countries, NORDEL, the installed capacity of the Icelandic power system in the year 2004 was 1475 MW. The installed capacity constitutes roughly 78% hydro power, 14% geothermal power and 8% fuel. The total generation of the system in 2004 was approximately 8.6 TWh of which roughly 83% where from hydro power, 17% where from geothermal power and generation from fuel was negligible. The peak load for 2004 was approximately 1 GW measured on the 17th of December. [3].

2.2 Network

The transmission system in Iceland is mainly operated at voltages from 66 kV to 220 kV, with the exception of a few 33 kV lines. The transmission system is built up of a meshed 220 kV network in the south part of the island connected to a 132 kV network that lies around the coast [4]. The transmission network can be viewed in figure 2.1.

Today a large part of the installed capacity of the system lies in the 220 kV network, thus making it a strong part of they system. In the 132 kV ring network there is relatively less installed capacity making it the weaker part of the system. Installed capacity in the system can be viewed in figure 2.2.

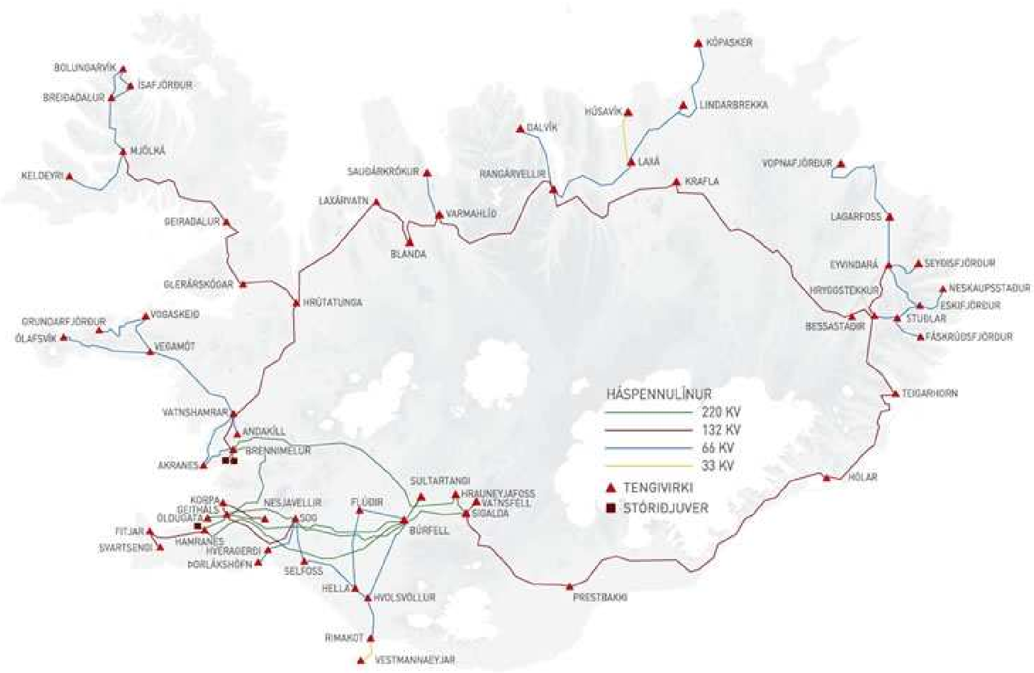

Figure 2.1: The Icelandic transmission system in 2005 [4] (triangles = substations, rectangles = heavy industry)

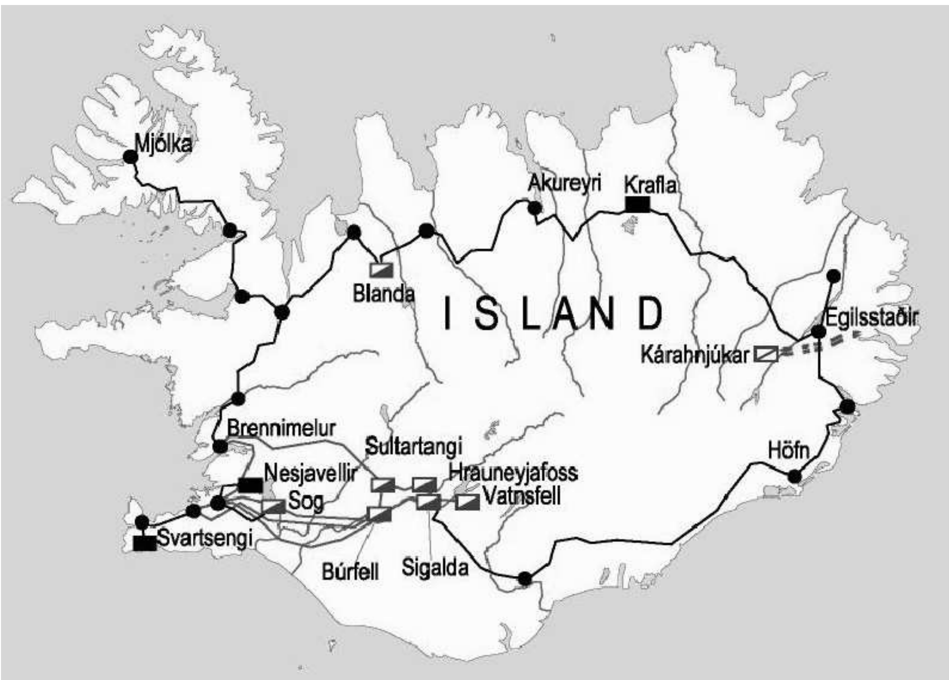

Figure 2.2: Installed capacity in Iceland (incl. Kárahnjúkar, 2007) [3] (Filled rectangles = geothermal, Half filled rectangles = hydro)

2.3 Load

The energy consumption divided by sectors can be viewed in figure 2.3. The main consumer is industry, consisting mostly of ferro-silicon and aluminum industry. The main load center is in the south part of the island in the vicinity of the capital, Reykjavík.

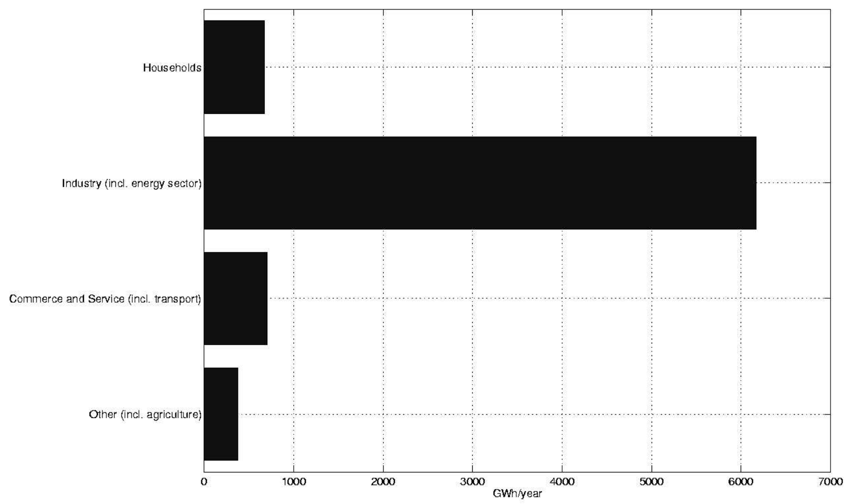

Figure 2.3: The energy consumption in Iceland 2004 [3]

2.4 Near future

As of today four power plants are under construction, three geothermal and one hydro power. The capacity of the geothermal plants is 210 MW. The capacity of the hydro power plant, called Kárahnjúkar, is 690 MW with an estimated annual generation of 4.600 GWh. The geothermal plants will be put on line from 2005 to 2006 and Kárahnjúkar in 2007.

The increase in installed geothermal capacity, which is located in the south, is to meet increase in the ferro-silicon and aluminum industry. Today this industry is centralized in the south part of the island near Reykjavík. The increase in hydro power, which is located in the east, is to meet the demand from a new aluminum plant of 320.000 tons to be started there in 2007 [3].

Chapter 3

Power system oscillations

The capacity of the Icelandic power system is, as has been mentioned, being increased significantly in an otherwise weak network. Areas with large capacity connected by weak ties have been known to cause oscillations. This chapter addresses the concept of power system stability, especially rotor angle stability and what kind of oscillations can be expected.

3.1 Power system stability

Power system stability is defined as [5]:

> Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.

Stability can be more precisely classified as:

- Rotor angle stability
- Frequency stability
- Voltage stability

The concept of rotor speed stability has also recently been proposed in [6]. A more in depth definition can be viewed in figure 3.1.

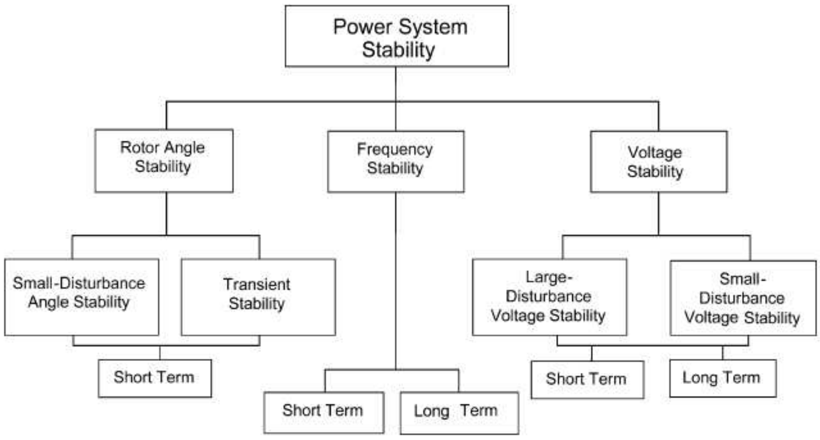

Figure 3.1: Classification of power system stability [5]

3.2 Rotor angle stability

Rotor angle stability implies that all synchronous machines, in a power system, maintain synchronism after a disturbance. Rotor angle stability is thus dependent on mechanical torque and electrical torque remaining or being restored to equilibrium at each machine. Meaning that the speed of the rotor and the angle between the stator and rotor magnetic fields are constant. Disturbances can cause either acceleration or deceleration of the rotor or even a slip in the synchronization of the fields causing the machine to fall out of synchronism with the rest of the system. If a machine looses synchronism it is disconnected from the system.

Rotor angle stability can be split up into two categories:

- Small signal stability
- Large signal stability

Small signal stability is the ability of the power system to maintain synchronism after small disturbances. Large signal stability is the ability of the power system to maintain synchronism after large disturbances, this is often also termed as transient stability.

Small signal stability is the focus of this thesis. The disturbances in question are considered small enough in order to be able to linearize the system for the purpose of applying eigenanalysis. Small signal instability comes in two forms:

- Increase in rotor angle due to insufficient synchronizing torque.

- Rotor oscillations due to insufficient damping torque.

A disturbance in a power system can cause a change in the value of the angle ($\Delta\delta$) and speed ($\Delta\omega$). This in turn leads to a change in electrical torque (ΔT_e) defined by equation 3.1.

$$\Delta T_e = K_S \Delta\delta + K_D \Delta\omega \tag{3.1}$$

The $K_S \Delta\delta$ part is in phase with change in rotor angle, $\Delta\delta$. This part is called the synchronizing torque component and K_S, the synchronizing torque coefficient. The $K_D \Delta\omega$ part is in phase with change in speed $\Delta\omega$. This part is called the damping torque component and K_D, the damping torque coefficient.

Both parts of the electrical torque are important for system stability. Insufficient synchronizing torque leads to aperiodic drift in rotor angle and insufficient damping torque leads to oscillations. Instability due to insufficient synchronizing torque is usually seen in systems without active voltage regulators (AVR) whereas instability due to insufficient damping torque is seen in systems with AVR and is thus more common [1].

3.3 Types

The types of electro-mechanic oscillations usually encountered in modern power systems can be divided into four groups:

- Local modes (0.7-3 Hz)
- Inter area modes (0.1 to 0.7 Hz)
- Control modes ($>$ 4 Hz)
- Torsional modes ($>$ 4 Hz)

Local modes are located at a single power plant or in a small part of the power system. They imply oscillations between generators in the power plant, termed intra plant (1.5-3 Hz), or oscillations between the power plant as an aggregate with the neighboring parts of the system (0.7-1.5 Hz). Inter area modes imply oscillations between two groups of synchronous machines connected by weak transmission lines. The slowest inter area mode usually involves all generators in the system. Control modes imply oscillations due to control of synchronous machines (governors, exciters) or control of equipment such as HVDC and SVC. Torsional modes imply oscillations due to turbine-generator shaft system rotational components [1], [7], [8].

Chapter 4

Power system stabilizer

The concept of PSS has been introduced in order to add sufficient damping to oscillations in a power system. A PSS is a unit attached to controls of a generator. The following gives a short description of such control systems as well as a basic theory of a PSS and standardized models.

4.1 Generator controls

A modern power system relies heavily on control systems in order to operate securely. This includes speed governing and voltage regulation systems at many power plants. Governors adjust the flow to a turbine driving a generator, in order to keep rotor speed constant. AVR systems adjust the field current excitation in a generator, in order to keep terminal voltage constant.

The main purpose of these control systems is to act on dynamical changes in the system, such as in load, in order to minimize voltage and frequency changes. Thus their operation is essential in ensuring quality of supply by the power system.

AVR's are known to reduce damping of oscillations in a power system, due to their high gain negative feedback. In order to maintain stability, oscillations must decay. In order to add damping to oscillations a feedback through a power system stabilizer can be used [2].

4.2 Theory

Equation 3.1 in chapter 3 states that in order to improve damping, an electrical torque component in phase with deviation of rotor speed must be applied. Figure 4.1 provides a better visualization of equation 3.1. In this figure a block diagram of a single machine, infinite bus system without AVR can be viewed. Electrical torque is accomplished by feedback of $\Delta\delta$ (ΔT_{eo}) and $\Delta\omega$ (ΔT_{ep}) through the constants K_S and K_D. The purpose of a PSS is to add a modulating signal to the V_{ref} input of an AVR in order to add an electrical torque component in phase with rotor speed deviation. This is usually done by feedback through a filter with phase shaping characteristics.

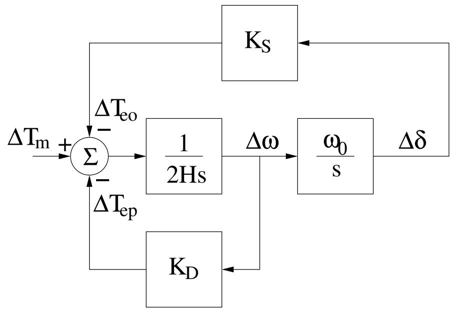

Figure 4.1: Single machine, infinite bus system without AVR

A more detailed version of the block diagram in figure 4.1 would include an AVR and a PSS. The block diagram for such a system can be viewed in figure 4.2. Since the purpose of the PSS is to add a damping torque in phase with

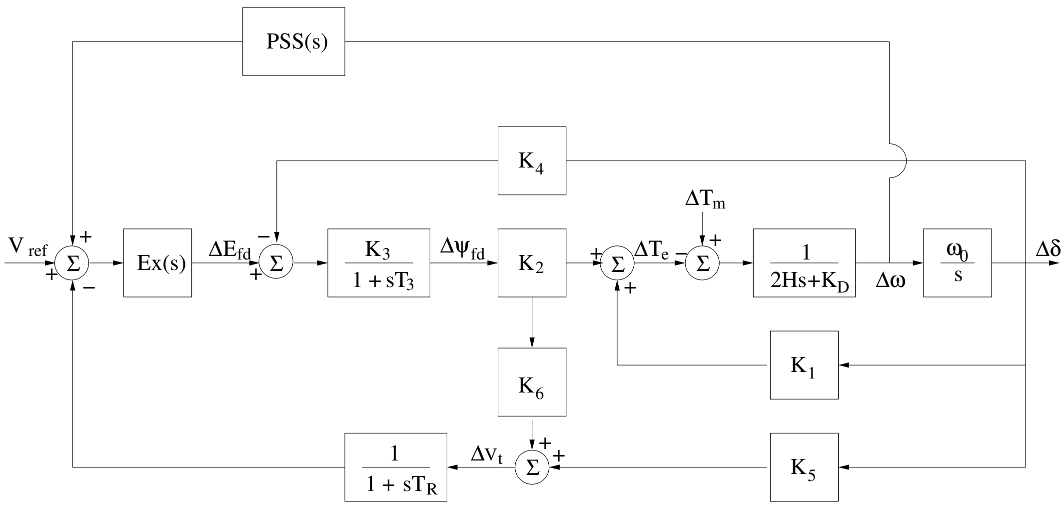

Figure 4.2: Single machine, infinite bus system with AVR and PSS

rotor speed deviation, it seems logical to use the rotor speed deviation as a feedback signal. In order to accomplish this the PSS has to compensate for the phase lag from the exciter, generator and power system, here denoted as GEP(s). If the phase characteristic of the PSS would be the exact inverse of the phase characteristic of GEP it would lead to pure damping at all oscillating frequencies. The amount of damping would be set by the gain of the PSS.

Figure 4.2 can be used to approximate the transfer function of GEP. By looking at the block diagram it can be seen that GEP is proportional to the closed loop AVR when the rotor speed is constant ($\Delta\omega = 0$). Which means that the characteristics of GEP(s) can be represented by equation 4.1.

$$GEP(s) = \frac{\Delta V_t}{V_{ref}} \tag{4.1}$$

Characteristics to be compensated for by the power system stabilizer can therefore be derived by looking at the transfer function from V_{ref} to terminal voltage (V_t). However, if a state space model is available for the system, another way would be to derive the transfer function from ΔV_{ref} to $\Delta\omega$ straight from the model. In this case the transfer function of GEP(s) is according to equation 4.2.

$$GEP(s) = \frac{V_{ref}}{\Delta\omega} \tag{4.2}$$

Equation 4.1 is on the other hand very valuable and comes into use when installing the PSS and determining its effect on the system [9], [1], [2].

4.3 Models

Two models of power system stabilizers have been standardized by IEEE Std 421.5-1992 [7]. These models are PSS1A and PSS2A and can be viewed in figures 4.3 and 4.4. The central part of both these stabilizer models are two lead-lag

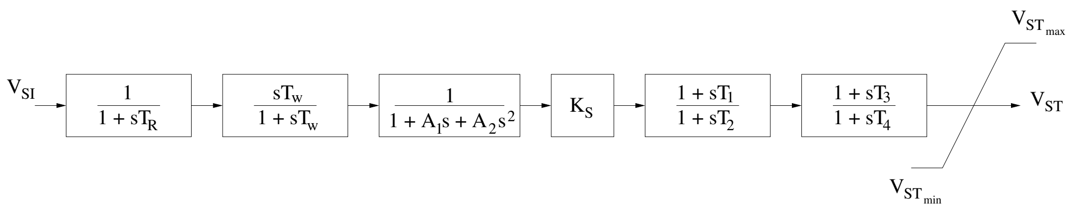

Figure 4.3: Power system stabilizer model PSS1A. From left to right the blocks are: Transducer, Washout filter, Torsional filter, Gain and Lead-Lag blocks

filters and a gain constant. The use of two lead-lag filters can give good results in matching phase characteristics over a relatively wide frequency range. This part of the stabilizer is used for compensation.

The PSS1A model in figure 4.3 usually uses rotor speed, bus frequency or active power as inputs. The first filter is a voltage transducer, the second filter is a washout filter and the third filter is a torsional filter. The voltage transducer is used to measure and scale down the feedback signal. The washout filter is

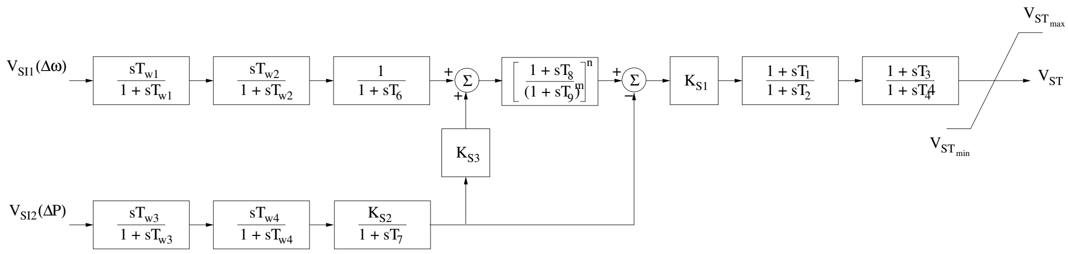

Figure 4.4: Power system stabilizer model PSS2A. From left to right the blocks are: Washout filters, Transducers, Crossover filter, Gain and Lead-Lag blocks

a high pass filter which is used in order to filter out slow changes in the input signal due to e.g. power ramping. The torsional filter is a low pass filter used in order to filter high frequency torsional oscillations due to angular motion of rotating elements. The problem with this stabilizer in practice is that it requires torsional filters at thermal plants, which introduces phase shift, and when using active power as input it becomes more sensitive to ramping. The PSS2A model was developed in order to overcome these problems. The PSS1A model is nevertheless very useful in general studies because of its simplicity.

The PSS2A model in figure 4.4 uses speed and active power as inputs in order to derive an input signal that is less sensitive to both torsional modes and ramping. For low frequencies the input to the stabilizer is speed while at high frequencies the input is the inverted integral of active power. The signal paths of this stabilizer incorporate similar filters as in the PSS1A model. That is the first two filters in each path are washout filters, followed by transducers. The filters between the two summation signs is a so called crossover filter which enables switching between the input signal depending on frequency [7], [1], [2].

Chapter 5

Modeling

To analyze a power system a detailed model is needed in order to fully comprehend its dynamics. This chapter gives information about the model used in this thesis. How the model is implemented in software is described as well as mathematical derivations from it. The complexity of the model and its derivations is also addressed.

5.1 Software

The power system simulator *Eurostag* 3.2 [10] was used for the analysis of the system. Load flow data and dynamic data was received in format from the power system simulator *PSS/E* 29 [11]. Load flow data and dynamic data was automatically converted to *Eurostag* form. All control equipment needed to be modeled and put in by hand in *Eurostag*. In [12] the process of converting *PSS/E* data regarding the Icelandic power system to *Eurostag* form is explained in detail as well as modeling of all control equipment and verification of the behavior. This process is not repeated here because only one model has been added.

5.2 Power System Model

The model of the Icelandic power system is a detailed model owned by the Icelandic transmission system operator, Landsnet. The transmission system voltages are mainly 220, 132, 66 kV plus very few 33 kV. The model also includes a few buses with distribution voltages as low as 0.415 kV. Generation voltages are 6.6 kV, 11 kV and 13.8 kV.

The complexity of the model can be viewed in table 5.1. As a test case a max load case for the year 2012 was used where 8 MW are exported from the east.

Components	Number
Buses	213
Lines	79
Transformers	142
Plants	20
Generators	46

Table 5.1: Model complexity

5.3 State space model

Models of power systems are described by a set of nonlinear differential algebraic (DAE) matrix equations on the form of equation 5.1.

$$\begin{aligned} \dot{x}_d &= f(x_d, x_a, u) \\ 0 &= g(x_d, x_a, u) \\ y &= h(x_d, x_a, u) \end{aligned} \tag{5.1}$$

Where x_d and x_a are the dynamic and algebraic state vectors respectively, u is the input vector and y is the output vector.

Small signal stability analysis handles small deviations from a stationary operating point. The model that is linearized around this point is therefore only valid close to this point. Deviations in the operating point are described in equation 5.2 where the operating point is marked with the superscript 0.

$$\begin{aligned} \Delta x_d &= x_d - x_d^0 \\ \Delta x_a &= x_a - x_a^0 \\ \Delta u &= u - u^0 \\ \Delta y &= y - y^0 \end{aligned} \tag{5.2}$$

The new state must apply with equation 5.1 and can thus be described as equation 5.3

$$\dot{x}_d = \dot{x}_d^0 + \Delta\dot{x}_d = f[(x_d^0 + \Delta x_d), (x_a^0 + \Delta x_a), (u^0 + \Delta u)] \tag{5.3}$$

and as the deviations are small, a Taylor series expansion can be applied to the nonlinear function $f(x, u)$. By neglecting the second and higher order powers of Δx and Δu we get equation 5.4.

$$\begin{aligned} \dot{x}_d = \dot{x}_d^0 + \Delta\dot{x}_d &= f[(x_d^0 + \Delta x_d), (x_a^0 + \Delta x_a), (u^0 + \Delta u)] \\ &= f(x_d^0, x_a^0, u^0) + \frac{\delta f}{\delta x_d}\Delta x_d + \frac{\delta f}{\delta x_a}\Delta x_a + \frac{\delta f}{\delta u}\Delta u \end{aligned} \tag{5.4}$$

and as $\dot{x}_d^0 = f(x_d^0, x_a^0, u^0)$, equation 5.5 can be derived.

$$\Delta\dot{x} = \frac{\delta f}{\delta x_d}\Delta x_d + \frac{\delta f}{\delta x_a}\Delta x_a + \frac{\delta f}{\delta u}\Delta u \tag{5.5}$$

The same expansion can be applied to the functions g and h so a linear DAE matrix equation is derived according to 5.6.

$$\begin{aligned} E_{dae}\begin{pmatrix} \Delta\dot{x}_d \\ \Delta\dot{x}_a \end{pmatrix} &= A_{dae}\begin{pmatrix} \Delta\dot{x}_d \\ \Delta\dot{x}_a \end{pmatrix} + B_{dae}\Delta u \\ \Delta y &= C_{dae}\begin{pmatrix} \Delta\dot{x}_d \\ \Delta\dot{x}_a \end{pmatrix} + D_{dae}\Delta u \end{aligned} \tag{5.6}$$

where

$$\begin{aligned} E_{dae} &= \begin{pmatrix} I & 0 \\ 0 & 0 \end{pmatrix} \\ A_{dae} &= \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix} = \begin{pmatrix} \frac{\delta f}{\delta x_d} & \frac{\delta f}{\delta x_a} \\ \frac{\delta g}{\delta x_d} & \frac{\delta g}{\delta x_a} \end{pmatrix} \\ B_{dae} &= \begin{pmatrix} B_1 \\ B_2 \end{pmatrix} = \begin{pmatrix} \frac{\delta f}{\delta u} \\ \frac{\delta g}{\delta u} \end{pmatrix} \\ C_{dae} &= \begin{pmatrix} C_1 & C_2 \end{pmatrix} = \begin{pmatrix} \frac{\delta h}{\delta x_d} & \frac{\delta h}{\delta x_a} \end{pmatrix} \\ D_{dae} &= D_1 = \frac{\delta h}{\delta u} \end{aligned} \tag{5.7}$$

All dynamic states can be merged into one single state vector Δx which makes the matrix equation according to 5.8 which is a very convenient and compact form.

$$E\Delta\dot{x} = A\Delta x \tag{5.8}$$

where

$$\Delta x = \begin{pmatrix} \Delta x_d \\ \Delta x_a \\ \Delta u \\ \Delta y \end{pmatrix}$$

In *Eurostag* the linearized state matrix A is exported in sparse form with the number of total variables as well as differential variables. The linearized system can therefore be formed according to equation 5.8. The matrices A_{dae}, B_{dae}, C_{dae} and D_{dae} can then be formed by splitting up the state matrix A.

State space methods are designed for ordinary differential (ODE) matrix equations Therefore the algebraic part of the DAE system has to be removed. This is done by substituting equation 5.9 into the DAE system.

$$\Delta x_a = -A_{22}^{-1}(A_{21}\Delta x_d + B_2\Delta u) \tag{5.9}$$

The result is an ODE system model according to equation 5.10.

$$\begin{aligned} \Delta \dot{x}_d &= A_{ode}\Delta x_d + B_{ode}\Delta u \\ \Delta y &= C_{ode}\Delta x_d + D_{ode}\Delta u \end{aligned} \tag{5.10}$$

where

$$\begin{aligned} A_{ode} &= A_{11} - A_{12}A_{22}^{-1}A_{21} \\ B_{ode} &= B_1 - A_{12}A_{22}^{-1}B_1 \\ C_{ode} &= C_1 - C_2A_{22}^{-1}A_{21} \\ D_{ode} &= D_1 - C_2A_{22}^{-1}B_2 \end{aligned}$$

With the ODE matrix equation 5.10, modal analysis can be applied to the system model [1],[13].

5.4 Complexity

Although the Icelandic power system is not relatively large by comparison to the rest of the NORDEL system, the model of the system is complex. All generators and respective models can be seen in table 5.2. As can be seen the model of the system has three types of generators, five types of governors, seven types of AVR and four types of PSS.

As was mentioned before, all models excluding generators needed to be modeled and put in by hand in *Eurostag*. The reason for using *Eurostag* instead of *PSS/E* is that more information is detained in the linearization process in *Eurostag* than in *PSS/E*. Therefore results of modal analysis are more accurate.

Number	ID	Location	Model	PSS	AVR	Governor
1011	1-2	Búrfell	GENSAE	-	EXPIC1	VTHGOV
1012	1-2	Búrfell	GENSAE	-	EXPIC1	VTHGOV
1013	1-2	Búrfell	GENSAE	-	EXPIC1	VTHGOV
1021	1	Sigalda	GENSAE	-	BBSEX1	VTHGOV
1022	1	Sigalda	GENSAE	-	BBSEX1	VTHGOV
1031	1	Hrauneyjar	GENSAL	STAB2A	IVOEX	WEHGOV
1032	1	Hrauneyjar	GENSAL	STAB2A	IVOEX	WEHGOV
1033	1	Hrauneyjar	GENSAL	STAB2A	IVOEX	WEHGOV
1041	1	Vatnsfell	GENSAL	-	IVOEX	HYGOV
1042	1	Vatnsfell	GENSAL	-	IVOEX	HYGOV
1051	1	Sultartangi	GENSAL	-	IVOEX	WEHGOV
1052	1	Sultartangi	GENSAL	-	IVOEX	WEHGOV
1111	1	Írafoss	GENSAL	-	IEEET4	VTHGOV
1112	1	Írafoss	GENSAL	-	IEEET4	VTHGOV
1113	1	Írafoss	GENSAL	-	IEEET4	VTHGOV
1121	1	Steingrímsstöð	GENSAL	-	IEEET1	VTHGOV
1122	1	Steingrímsstöð	GENSAL	-	IEEET1	VTHGOV
1131	1-3	Ljósafoss	GENSAL	-	IEEET1	VTHGOV
1141	1	Nesjavellir	GENROU	-	ESAC5A	TGOV7
1201	1-4	Hellisheiði	GENROU	-	ESAC5A	TGOV7
2021	1-2	Ísal	GENROU	-	IEEET1	-
2332	1	Reykjanes	GENROU	-	IEEET1	TGOV7
2336	1	Reykjanes	GENROU	-	IEEET1	TGOV7
3121	1	Vatnshamrar	GENROU	-	IEEET1	-
3303	1-2	Mjólká	GENSAL	-	SCRX	-
4031	1	Blanda	GENSAL	IVOST	IVOEX	BLANGV
4032	1	Blanda	GENSAL	IVOST	IVOEX	BLANGV
4033	1	Blanda	GENSAL	IVOST	IVOEX	BLANGV
4061	1	Krafla	GENROU	STAB4	ESAC5A	TGOV7
4062	1	Krafla	GENROU	STAB4	ESAC5A	TGOV7
4071	1	Bjarnarflag	GENROU	-	IEEET1	TGOV7
4101	1	Laxá	GENSAL	-	IEEET1	HYGOV
5061	1	Kárahnjúkar	GENSAE	PSS2A	BBSEX1	BLANGV
5062	1	Kárahnjúkar	GENSAE	PSS2A	BBSEX1	BLANGV
5063	1	Kárahnjúkar	GENSAE	PSS2A	BBSEX1	BLANGV
5064	1	Kárahnjúkar	GENSAE	PSS2A	BBSEX1	BLANGV
5065	1	Kárahnjúkar	GENSAE	PSS2A	BBSEX1	BLANGV
5066	1	Kárahnjúkar	GENSAE	PSS2A	BBSEX1	BLANGV
5201	1	Lagarfoss	GENSAL	-	IEEET1	-

Table 5.2: Generators and associated models

5.5 Matlab model

The linearized DAE model of the system when imported to *Matlab* [14], has without any simplifications 833 dynamic states and 541 algebraic equations. The ODE model obtained from reduction of the DAE model is a so called multiple input, multiple (MIMO) output system in contrast to simpler control systems which are single input, single (SISO) output. To increase damping in the system by use of PSS, the control of each generator locally is affected in order damp oscillations that can be system wide. The complexity of the model makes it non obvious how damping can be increased, how it works and where to locate it.

Chapter 6

Modal analysis

An ODE model has been derived from a complex DAE model of a power system. A whole set of tools based on eigenanalysis can be applied to this system in order to analyze its dynamical behavior. An analysis of this sort is called modal analysis, as it identifies oscillating modes of the system. The first part of this chapter addresses the theory of modal analysis. Then requirements on damping are set as well as what test cases to use in the analysis. The remains of the chapter include the results of modal analysis.

6.1 Theory

A linearized ODE model of the power system is expressed by equation 6.1, as was derived in chapter 5.

$$\begin{aligned} \Delta\dot{x}_d &= A_{ode}\Delta x_d + B_{ode}\Delta u \\ \Delta y &= C_{ode}\Delta x_d + D_{ode}\Delta u \end{aligned} \tag{6.1}$$

where:

- Δx_d is the state vector with dimension n
- Δy is the output vector with dimension m
- Δu is the input vector with dimension r
- A_{ode} is the state matrix with dimension n x n
- B_{ode} is the input matrix with dimension n x r
- C_{ode} is the output matrix with dimension m x n
- D_{ode} is the feed forward matrix with dimension m x r

The right eigenvectors and the eigenvalues of the state matrix can be calculated according to equation 6.2. The left eigenvectors and the eigenvalues of the state matrix can be calculated according to equation 6.3. The normalized relationship between the right and left eigenvectors is expressed by equation 6.4

$$A_{ode}\phi_i = \lambda_i\phi_i \qquad i = 1, 2\ldots, n \tag{6.2}$$

$$\psi_i A_{ode} = \lambda_i\psi_i \qquad i = 1, 2\ldots, n \tag{6.3}$$

$$\psi_i\phi_i = 1 \qquad i = 1, 2\ldots, n \tag{6.4}$$

By summarizing equations 6.2 to 6.4 equations 6.5 to 6.7 can be derived.

$$A_{ode}\Phi = \Phi\Lambda \tag{6.5}$$

$$\Psi A_{ode} = \Lambda\Psi \tag{6.6}$$

$$\Psi\Phi = I \tag{6.7}$$

Where Φ is the matrix with all right eigenvectors, Ψ is the matrix with all left eigenvectors and Λ is the matrix with all eigenvalues as diagonal elements. By transforming the state vector with Φ, any coupling between state variables can be removed. The transformation is expressed by equation 6.8.

$$\Delta x_d = \Phi\Delta z \tag{6.8}$$

If we apply this transformation to equation 6.1 we will get a transformed system described by equation 6.9.

$$\begin{aligned} \Delta\dot{z} &= \Lambda\Delta z + \Phi^{-1}B_{ode}\Delta u \\ \Delta y &= C_{ode}\Phi\Delta z + D_{ode}\Delta u \end{aligned} \tag{6.9}$$

The state equations have then been decoupled, where each row now stands for a certain mode of the system. A block diagram of equation 6.9 can be viewed in figure 6.1.

A few interesting properties can be derived from the equations stated above. It can be seen from equation 6.8 that a right eigenvector gives a measure of how active each state variable is when a mode is excited. This is called mode shape. Another interesting property is the so called participation matrix P where each column vector is the element by element product of left and right eigenvectors for each eigenvalue. Each element $p_{ki} = \phi_{ki}\psi_{ik}$ is a participation factor giving information about participation of the kth state variable in the ith mode.

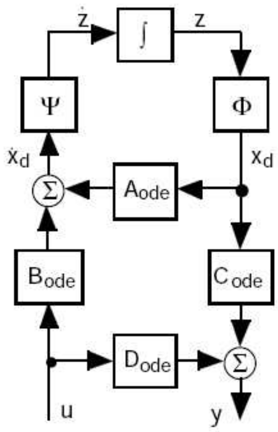

Figure 6.1: A block diagram for equation 6.9

By analyzing equation 6.9 and figure 6.1 it can be seen that the inputs to the system act through the matrix $\Phi^{-1}B$ and thus this matrix can be used in determining mode controllability. This is referred to as the mode controllability matrix. It can also be seen that the outputs of the system act through the matrix $C\Phi$ and thus this matrix can be used in determining observability of a mode in the output. This is referred to as the mode observability matrix. If a partial fraction expansion is applied to a transfer function it can be split up into modes multiplied with a constant called residue. Residue is the multiplication of observability and controllability and gives the sensitivity of a mode to feedback of a transfer function output to its input.

By using these properties, an in depth small signal stability analysis can be applied to the power system [1], [2].

6.2 Damping requirements

In order to apply modal analysis to a power system requirements on damping of its oscillation modes have to be set to be able to interpret the result. Oscillations in power systems are required to be damped in order to maintain stability. Halving time of 10 s has been used in design of damping controls in the NORDEL system, which means that the real part of the eigenvalue has to be more negative than -0.0693. Another rule of thumb is to require a damping ratio of 0.05 which gives a small safety margin. Often a damping ratio of 0.15 is required in large interconnected systems. A visual representation of the damping requirements can be viewed in figure 6.2 [2].

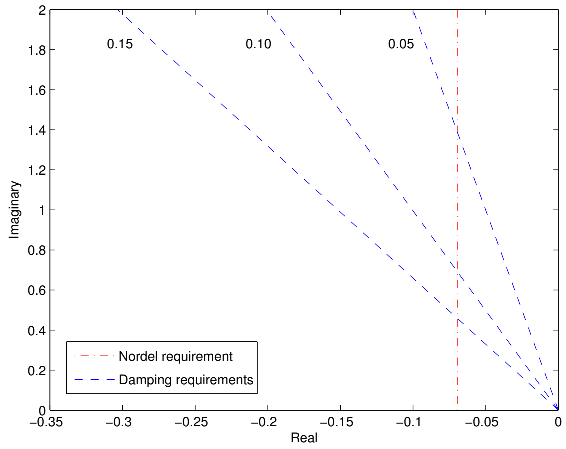

Figure 6.2: A visualization of damping requirements

6.3 Test cases

Three test cases will be used in the analysis of the system:

- Case 0: A short circuit at Blanda ring connection, cleared after 100 ms
- Case 1: A short circuit on the transmission line from Brennimelur to Vatnshamrar, line is opened after 100 ms
- Case 2: A short circuit on the transmission line from Krafla to Fljótsdalur, line is opened after 100 ms

A visualization of these test cases can be viewed in figure 6.3.

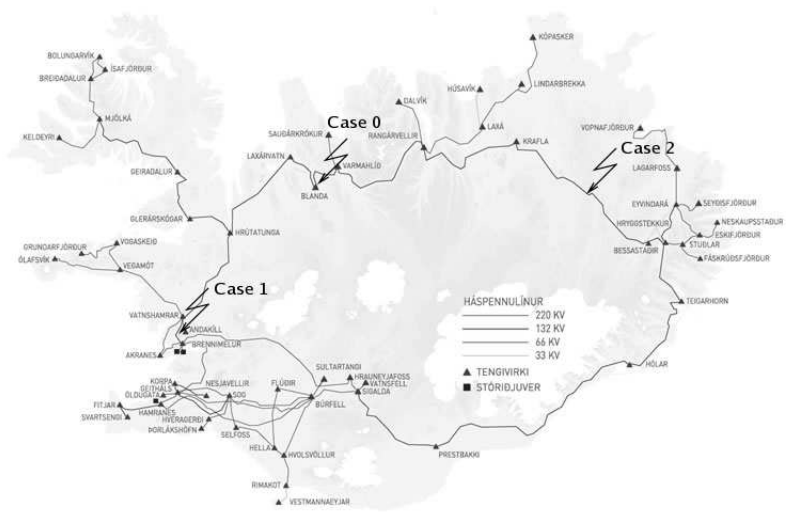

Figure 6.3: A visualization of test cases

6.4 Preliminary analysis

The eigenvalues of the linearized state matrix A_{ode} of the intact system model with less damping than 10% are displayed in table 6.1. There are seven modes with negative damping. Negative damping means that the oscillation will grow if the corresponding mode is excited, which means that it will lead to instability of the system. The eigenvalues with negative damping need further analysis before analyzing the rest of the system.

Mode	Eigenvalue	Frequency (Hz)	Damping
1	-0.2447±j14.8349	2.3614	0.0165
2	-0.2447±j14.8349	2.3614	0.0165
3	-1.0816±j13.8056	2.2040	0.0781
4	-0.6964±j14.2710	2.2740	0.0487
5	-0.6964±j14.2710	2.2740	0.0487
6	-1.0349±j12.6078	2.0133	0.0818
7	-0.4110±j10.4818	1.6695	0.0392
8	-0.5928±j10.1323	1.6154	0.0584
9	0.4957±j9.2383	1.4724	**-0.0536**
10	0.6836±j9.4606	1.5096	**-0.0721**
11	-0.9061±j9.2932	1.4861	0.0970
12	-0.5960±j8.8089	1.4052	0.0675
13	-0.4967±j6.2281	0.9944	0.0795
14	-0.0925±j2.6777	0.4264	0.0345
15	0.3346	0.0532	**-1.0000**
16	0.3223	0.0513	**-1.0000**
17	0.3227	0.0514	**-1.0000**
18	0.0083	0.0013	**-1.0000**
19	0.0062	0.0010	**-1.0000**

Table 6.1: Eigenvalues of the state matrix A_{ode} with less than 10% damping

The mode shapes for modes 9 and 10 can be viewed in figures 6.4 and 6.5. The bar plot on the left is a rotated version of the mode shape in order to identify those units oscillating against each other. The compass plot to the right displays the elements of the mode shape and their angles to complement the bar plot. In this way it can be determined which units are oscillating and what units they are oscillating against. In figure 6.4 it can be seen that the two generators at Vatnsfell oscillate against other generators in the local area of the 220 kV network. In figure 6.5 it can be seen how the two generators oscillate against each other in intra plant fashion. These modes can therefore be classified as local modes at the Vatnsfell power plant. In order to damp these modes a PSS could be installed.

The mode shape for mode 15 can be viewed in figure 6.6. The mode shapes for modes 16 to 19 are very similar and therefore need no further clarification. These modes are local to the power plants Búrfell and Ljósafoss. In modeling of generators and controls for these two power plants there are generators connected to common bus. Thus the AVR's are controlling the voltage at the same bus. The reason for the oscillations could be that the regulators are competing against each other, which in turn causes these unstable modes. The question is if this can happen in daily operation of the system or if it is just in the model. Most likely this is not a problem in the actual equipment and so this is only a minor flaw in the modeling of the system.

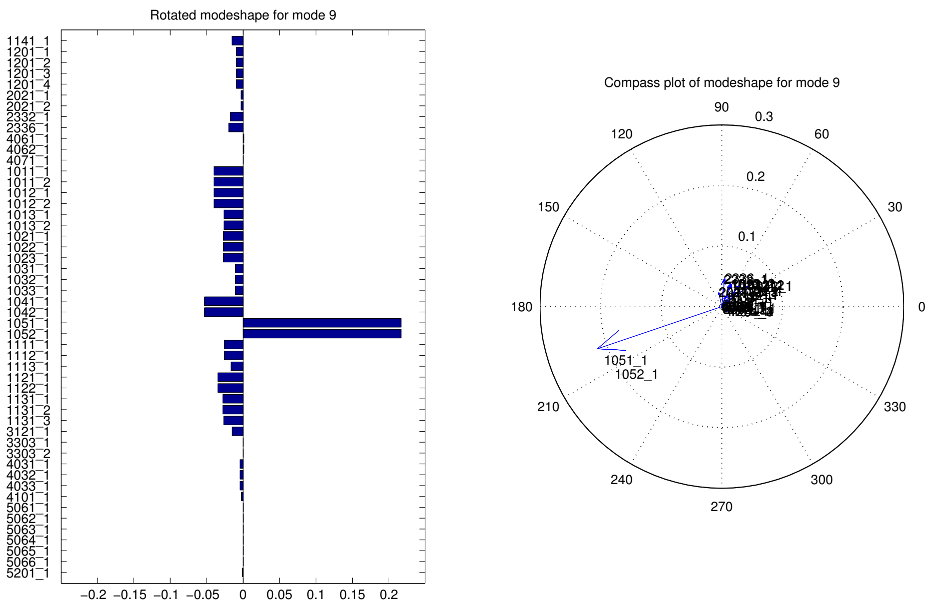

Figure 6.4: The mode shape for mode 9. Generators at Vatnsfell oscillate against generators in the 220 kV network

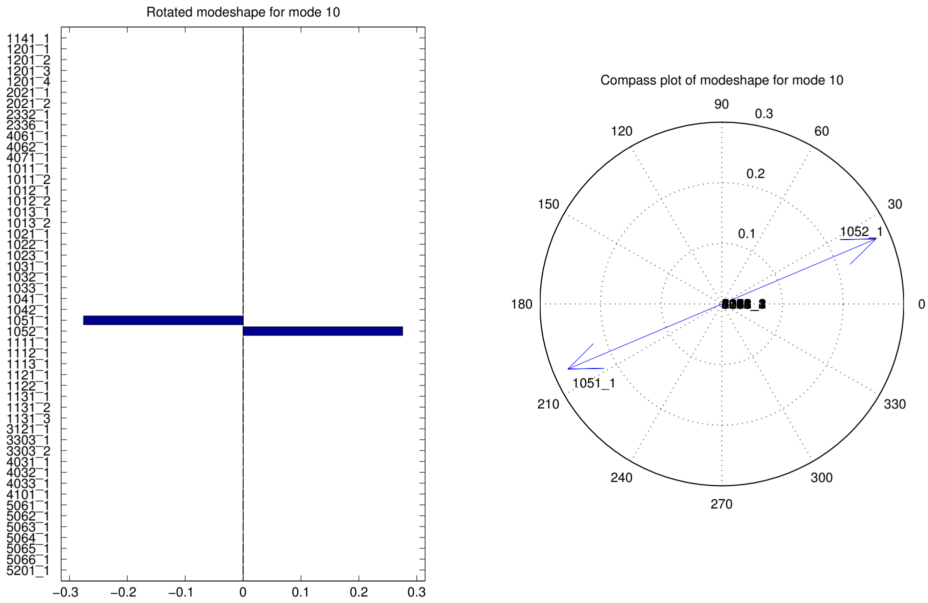

Figure 6.5: The mode shape for mode 10. Generators oscillate against each other

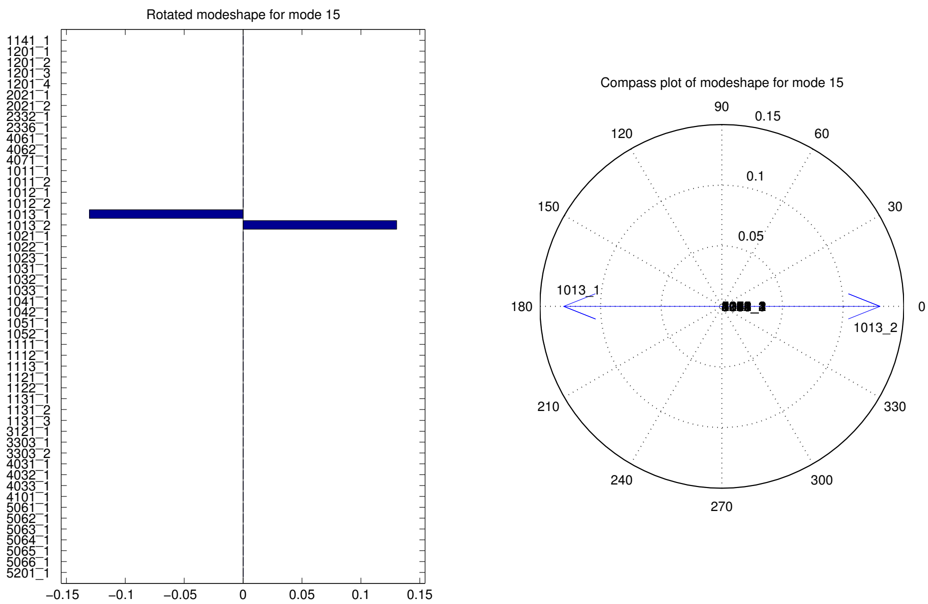

Figure 6.6: The mode shape for mode 15. Generators at Hrauneyjar oscillate against each other

The step is taken here to aggregate generators, connected to common bus, that have AVR's causing oscillations. This is done in order to stabilize the model. This has negligible effect on the other modes and is consistent with the fact that in local modes and inter area modes, generator groups oscillate against each other as aggregates.

6.5 Analysis with existing PSS's

Test cases will be analyzed using the system model were generators connected to a common bus at Búrfell and Ljósafoss have been aggregated. The existing PSS's in the system are also turned on. Modal analysis is performed at steady state after fault clearing for:

- 0: Intact network
- 1: Ring open between Brennimelur and Vatnshamrar
- 2: Ring open between Krafla and Fljótsdalur

6.5.1 Case 0

The eigenvalues of the state matrix with less damping than 10% can be viewed in table 6.2. The modes with less damping than 5% are modes 1-2, 4-5, 7, 9-10 and 13. Modes 9-10 are the unstable local modes at Vatnsfell that have already been analyzed.

Mode	Eigenvalue	Frequency (Hz)	Damping
1	-0.2447±j14.8349	2.3614	0.0165
2	-0.2447±j14.8349	2.3614	0.0165
3	-1.1353±j13.8349	2.2093	0.0818
4	-0.6964±j14.2710	2.2740	0.0487
5	-0.6964±j14.2710	2.2740	0.0487
6	-1.0350±j12.6079	2.0134	0.0818
7	-0.4112±j10.4818	1.6695	0.0392
8	-0.6122±j10.1293	1.6151	0.0603
9	0.4902±j9.2201	1.4695	**-0.0531**
10	0.6836±j9.4606	1.5096	**-0.0721**
11	-0.5963±j8.8095	1.4053	0.0675
12	-0.4967±j6.2282	0.9944	0.0795
13	-0.0811±j2.6906	0.4284	0.0301

Table 6.2: Case 0: Eigenvalues with less than 10% damping

Modes 1-2 are intra plant modes at Blanda power plant. The mode shape for mode 1 can be viewed in figure 6.7. In mode 1, generators 4031_1 and 4032_1 oscillate against 4033_1 and in mode 2, generator 4031_1 oscillates against 4032_1. Both of these modes are under damped.

Modes 4-5 are intra plant modes at Hrauneyjar. The mode shape for mode 4 can be viewed in figure 6.8. In mode 4, generator 1031_1 oscillates against 1032_1 and in mode 5, generators 1031_1 and 1033_1 oscillate against 1032_1. These modes are already fairly well damped.

Mode 7 is a local mode where generators at Blanda and Laxá oscillate against each other. The mode shape of this mode can be viewed in figure 6.9. This mode needs increased damping.

Finally, mode 13 is an inter area mode, where all the generators in the system take part. The mode shape can be viewed in figure 6.10. It can be seen from this figure that the generators at Káranjúkar oscillate against generators in the 220 kV network. This mode is under damped and needs additional damping.

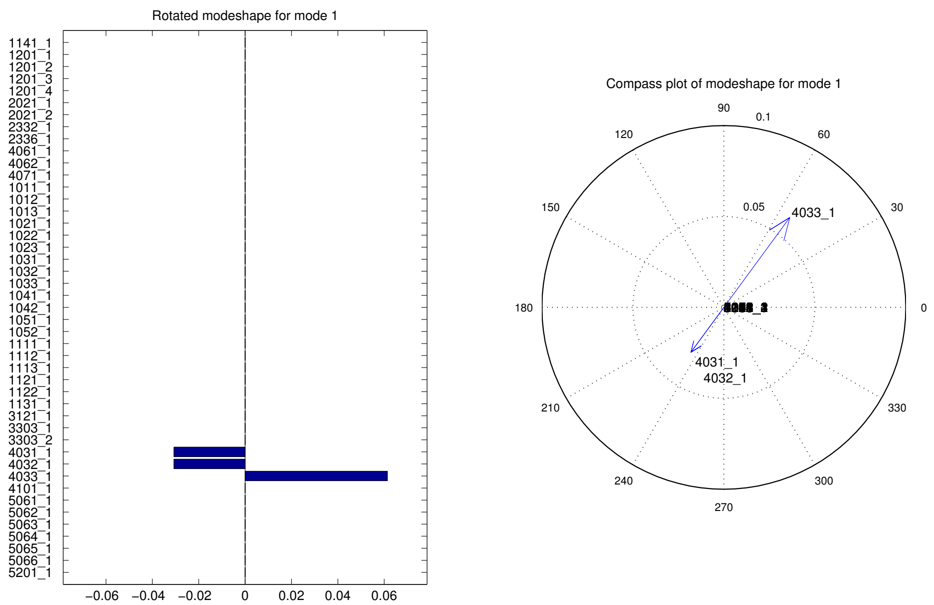

Figure 6.7: The mode shape for mode 1. Generators at Blanda oscillate against each other

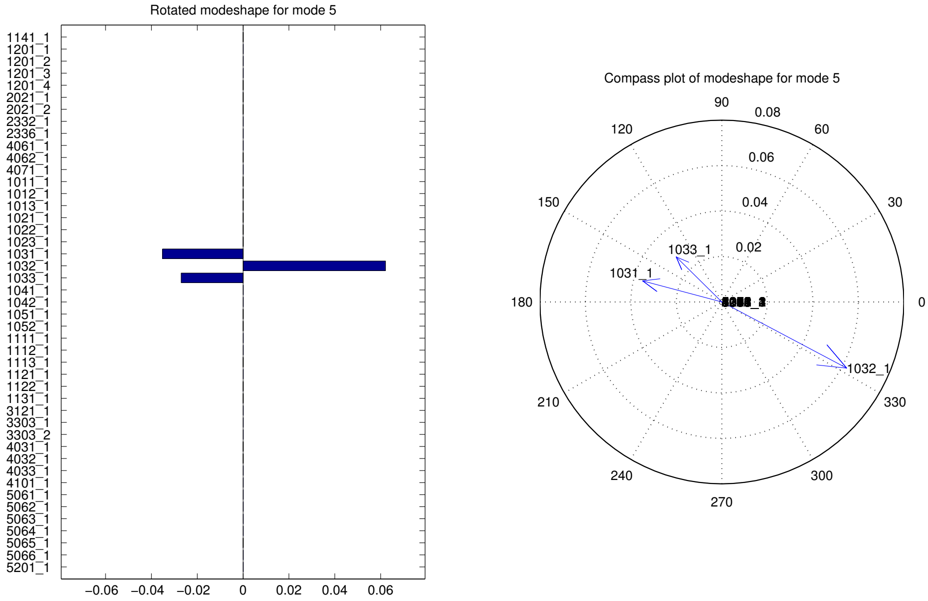

Figure 6.8: The mode shape for mode 5. Generators at Hrauneyjar oscillate against each other

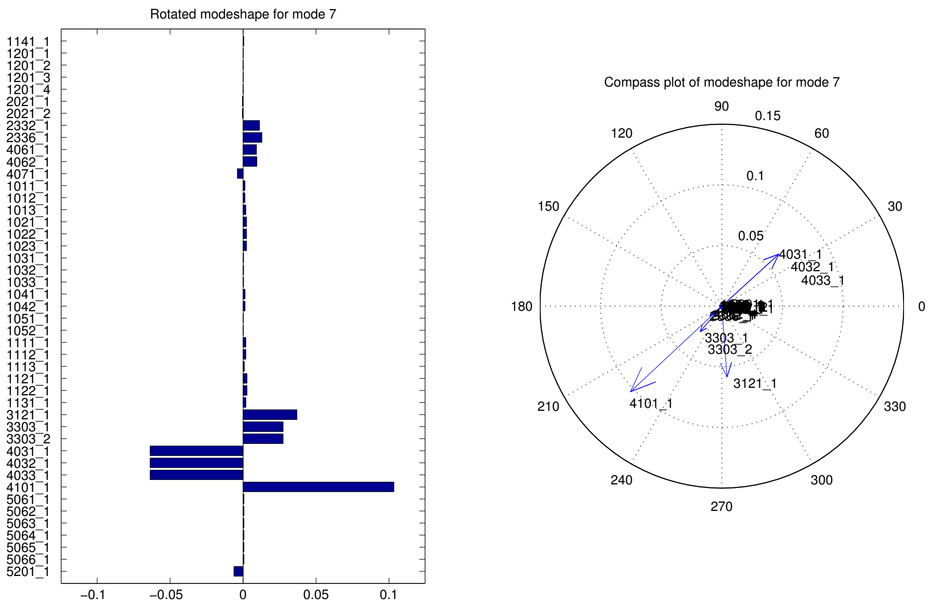

Figure 6.9: The mode shape for mode 7. Generators at Blanda oscillate against generator at Laxá

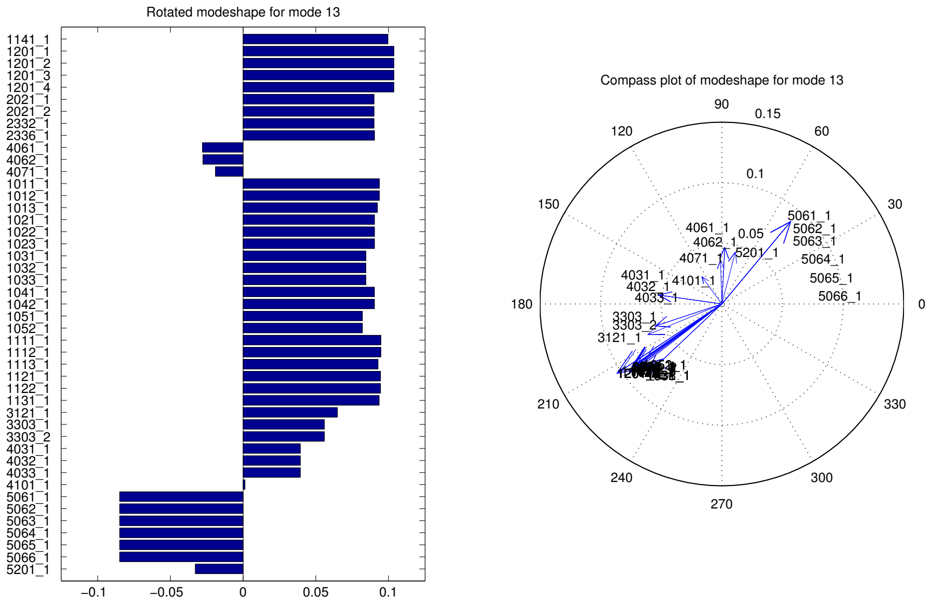

Figure 6.10: The mode shape for mode 13. Kárahnjúkar oscillate against generators in the 220 kV network

6.5.2 Case 1

The eigenvalues of the state matrix A_{ode} with less than 10% damping can be viewed in table 6.3. The modes with less than 5% damping are the same modes as in case 0. Their mode shapes are the same so they are not shown here. Damping has been increased for all modes except the unstable local mode at Vatnsfell and the inter area mode.

Damping of modes 1-2 and 4-5 has increased slightly. Damping of modes 4-5 is now nearer to 5%. Modes 1-2 on the other hand are still underdamped. The damping of mode 7 has changed the most and it is now more than 5%. The damping of the intra plant modes at Vatnsfell is around the same and still negative.

Attention has to be paid to the inter area mode which now has negative damping. If this mode would be excited under these conditions it would grow and cause instability. The damping of this mode has to be improved.

Mode	Eigenvalue	Frequency (Hz)	Damping
1	-0.2543±j14.8275	2.3602	0.0172
2	-0.2543±j14.8275	2.3602	0.0172
3	-1.1521±j13.8249	2.2079	0.0830
4	-0.7085±j14.2450	2.2700	0.0497
5	-0.7085±j14.2450	2.2700	0.0497
6	-1.0363±j12.6017	2.0124	0.0820
7	-0.6039±j10.2899	1.6405	0.0586
8	-0.6130±j10.1211	1.6138	0.0605
9	0.4923±j9.2381	1.4724	**-0.0532**
10	0.6898±j9.4795	1.5127	**-0.0726**
11	-0.7155±j8.8510	1.4133	0.0806
12	-0.5556±j6.1817	0.9878	0.0895
13	0.0089±j1.6273	0.2590	**-0.0054**

Table 6.3: Case 1: Eigenvalues with less than 10% damping

6.5.3 Case 2

The eigenvalues of the state matrix A_{ode} with less than 10% damping can be viewed in table 6.4. The modes with less than 5% damping are the same modes as seen in case 0 and 1, except that mode 13 is new and has negative damping.

Damping of modes 1-2 and 4-5 has decreased slightly. Modes 1-2 have worse damping than in case 0 but modes 4-5 have similar damping. Mode 7 is again with less damping than 5% and even less than in case 0. The unstable intra plant modes at Vatnsfell have the same damping as before.

The system now has two unstable inter area modes, that is modes 13-14. Their mode shapes can be viewed in figures 6.11 and 6.12. From figure 6.11 it can be seen that the generators at Krafla, Laxá and Blanda oscillate against the generator in the 220 kV network. From 6.12 it can be seen that Kárahnjúkar and Lagarfoss oscillate against the rest of the system. Kárahnjúkar, Blanda and Krafla participate the most in this oscillation. These modes need to be damped.

Mode	Eigenvalue	Frequency (Hz)	Damping
1	-0.1633±j14.9020	2.3719	0.0110
2	-0.1633±j14.9020	2.3719	0.0110
3	-1.1362±j13.8301	2.2085	0.0819
4	-0.6966±j14.2683	2.2736	0.0488
5	-0.6966±j14.2683	2.2736	0.0488
6	-1.0374±j12.5967	2.0116	0.0821
7	-0.4489±j10.2772	1.6372	0.0436
8	-0.6129±j10.1193	1.6135	0.0605
9	0.4915±j9.2252	1.4703	**-0.0532**
10	0.6856±j9.4670	1.5107	**-0.0722**
11	-0.6885±j8.7047	1.3897	0.0788
12	-0.3903±j6.0436	0.9639	0.0644
13	0.1426±j3.0395	0.4843	**-0.0469**
14	0.0382±j2.0287	0.3229	**-0.0188**

Table 6.4: Case 2: Eigenvalues with less than 10% damping

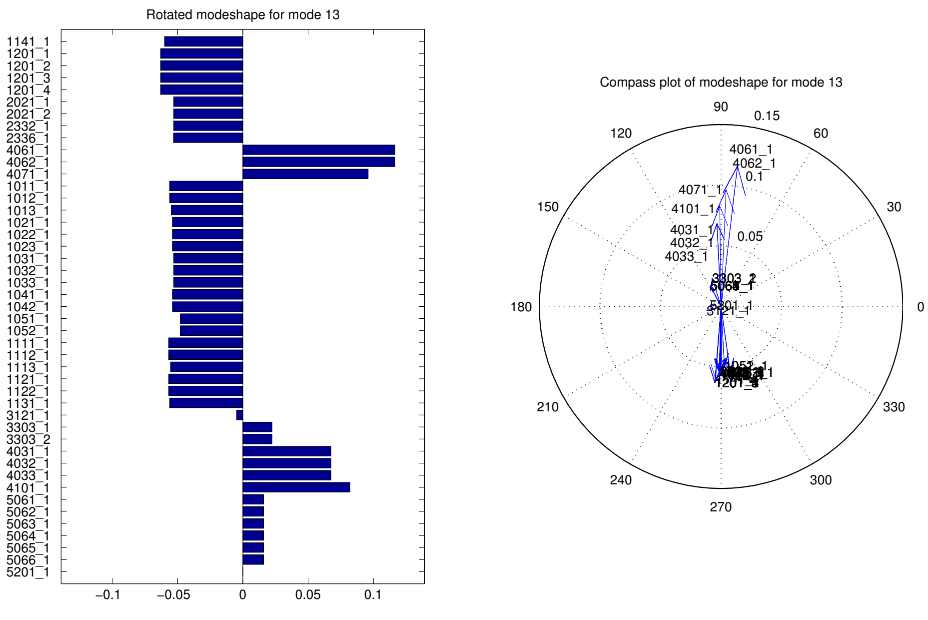

Figure 6.11: The mode shape for mode 13. Generators at Krafla, Laxá and Blanda oscillate against generators in the 220 kV network

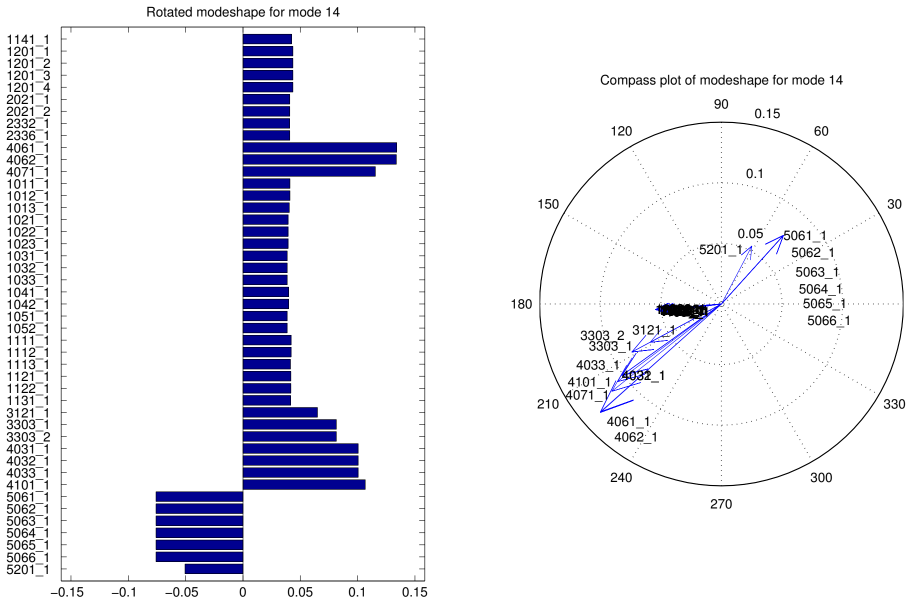

Figure 6.12: The mode shape for mode 14. Generators at Kárahnjúkar and Lagarfoss oscillate against rest of the system

6.5.4 Remarks

Modal analysis of the three test cases reveals that oscillations in the approximate frequency range of 0.26-2.37 Hz can be exited in the system. The intra plant mode at Vatnsfell is unstable in all cases and needs sufficient damping. The main inter area mode has either insufficient or negative damping in all cases and therefore needs more damping. Also a new inter area mode is introduced in case 2. The intra plant modes at Blanda are also under damped. The intra plant modes at Hrauneyjar and the local mode in the north with Blanda and Laxá only need slightly more damping in order to pass the 5% limit.

The primary goal would be to add sufficient damping to all inter area modes. The power plants that participate the most in the main inter area mode are Kárahnjúkar and the power plants in the 220 kV network. Tuning the PSS's at Kárahnjúkar and Hrauneyjar should therefore add damping to this mode. A PSS has to be added to Vatnsfell in order to damp the intra plant mode there. Also the PSS's at Blanda need to be re tuned in order to damp the intra plant mode there. The only PSS that doesn't seem to need retuning is the PSS at Krafla.

As all PSS's except one seem to need retuning it seems logical to design a new damping strategy by retuning and adding PSS's at all the locations mentioned above. As all PSS's would be re tuned it would be logical to tune them for a system without the existing PSS's. Modal analysis of the system without existing PSS's would therefore form a basis for such strategy. The following section describes modal analysis of case 0 without existing PSS's.

6.6 Analysis without existing PSS's

The eigenvalues of the state matrix A_{ode} with less than 10% damping in case 0 without existing PSS's can be viewed in table 6.5. In this case the modes without sufficient damping are modes 3-9 and 12-13.

Mode	Eigenvalue	Frequency	Damping
1	-1.0347±j12.6080	2.0134	0.0818
2	-0.6045±j10.1202	1.6135	0.0596
3	0.9314±j9.3052	1.4884	**-0.0996**
4	0.6837±j9.4605	1.5096	**-0.0721**
5	1.1612±j9.4272	1.5117	**-0.1222**
6	1.1612±j9.4272	1.5117	**-0.1222**
7	-0.3798±j9.3217	1.4848	0.0407
8	0.1796±j8.8762	1.4130	**-0.0202**
9	-0.2502±j7.2300	1.1514	0.0346
10	-0.5488±j7.2904	1.1636	0.0751
11	-0.4644±j6.2603	0.9991	0.0740
12	0.0238±j5.4183	0.8624	**-0.0044**
13	0.2060±j2.9625	0.4726	**-0.0694**

Table 6.5: Case 0, no PSS: Eigenvalues with less than 10% damping

Mode 3 is a local mode where the generators at Hrauneyjar seem to be oscillating against the generators at Vatnsfell. Mode 4 is an intra plant mode at Vatnsfell, modes 5-6 are intra plant modes at Hrauneyjar and mode 7 is a local mode in the north where Blanda oscillates against Laxá. Modes 3-4, 5-6 and 7 are similar to modes 9-10, 4-5 and 7 respectively for the analysis with existing PSS's.

The mode shapes for the rest of the modes with less than 5% damping can be viewed in figures 6.13 to 6.16. From the mode shape of mode 8 it can be seen that this is a local mode in the 220 kV network, where Hrauneyjar and Vatnsfell oscillate against the other generators. Mode 9 is a local mode in the north with Krafla and Mjólká oscillating against Blanda. In mode 12 Krafla, Mjólká, Blanda and Laxá oscillate against the rest of the system. Finally mode 13 is an inter area mode where Krafla, Laxá, Kárahnjúkar and Lagarfoss oscillate against the rest of the system. Blanda is seen to participate very little in this mode.

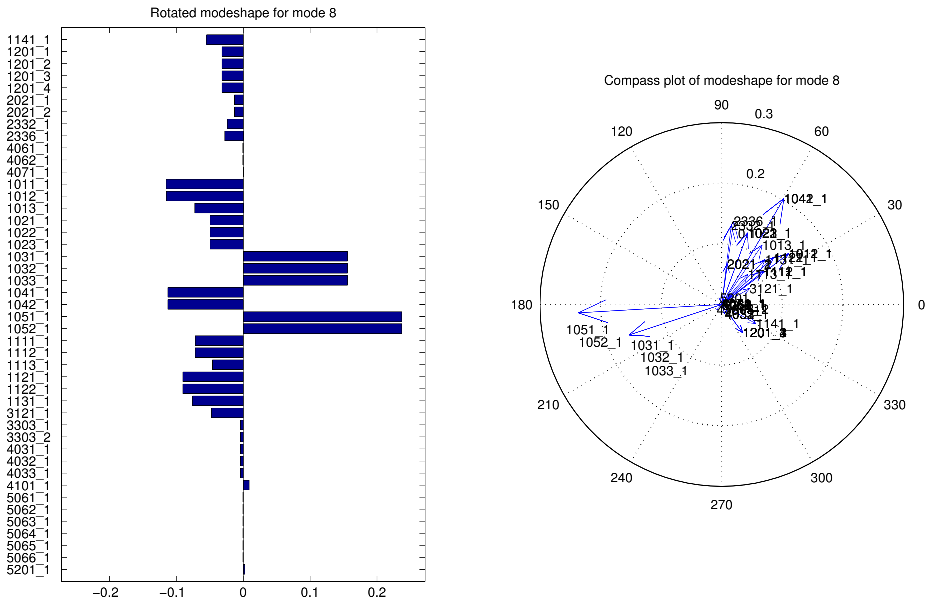

Figure 6.13: The mode shape for mode 8

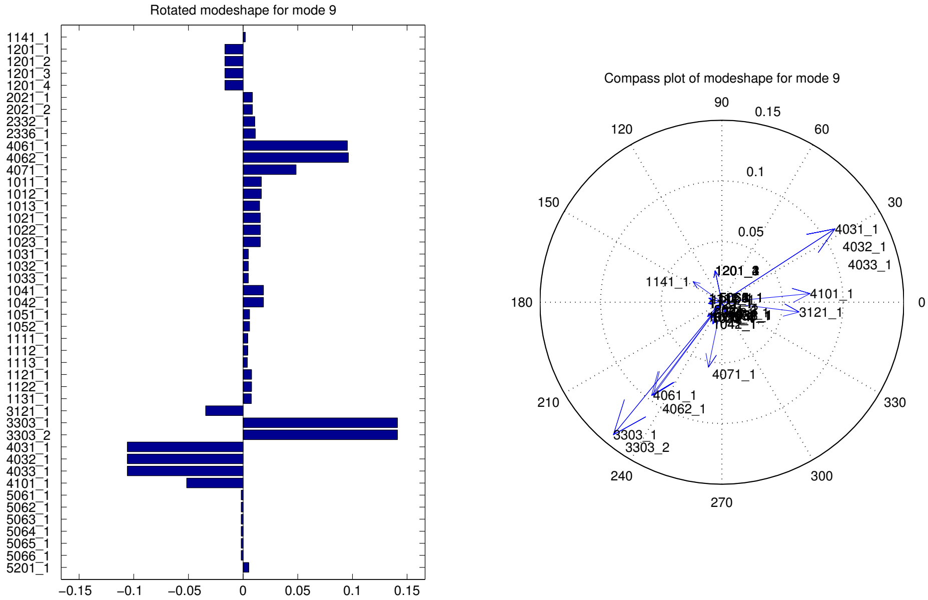

Figure 6.14: The mode shape for mode 9

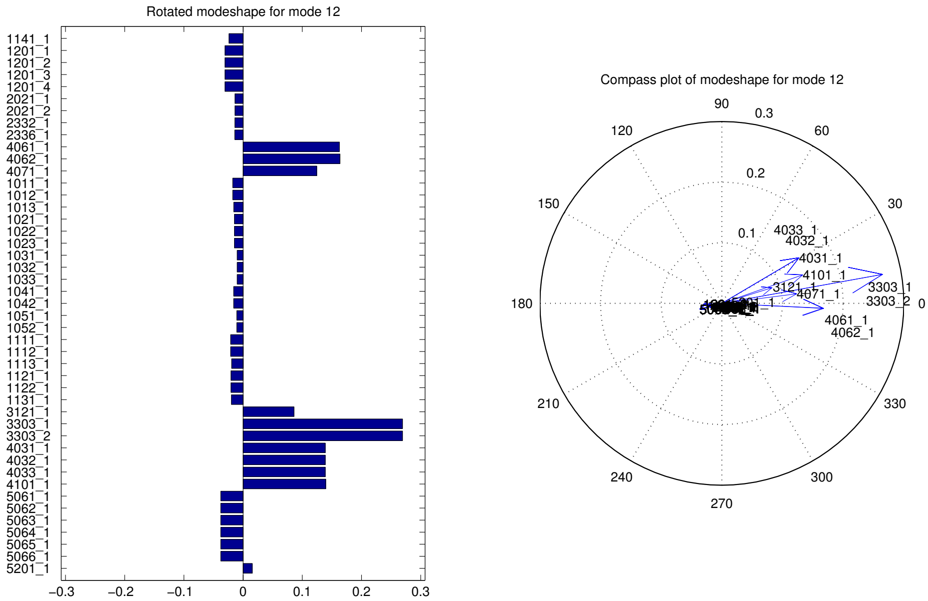

Figure 6.15: The mode shape for mode 12

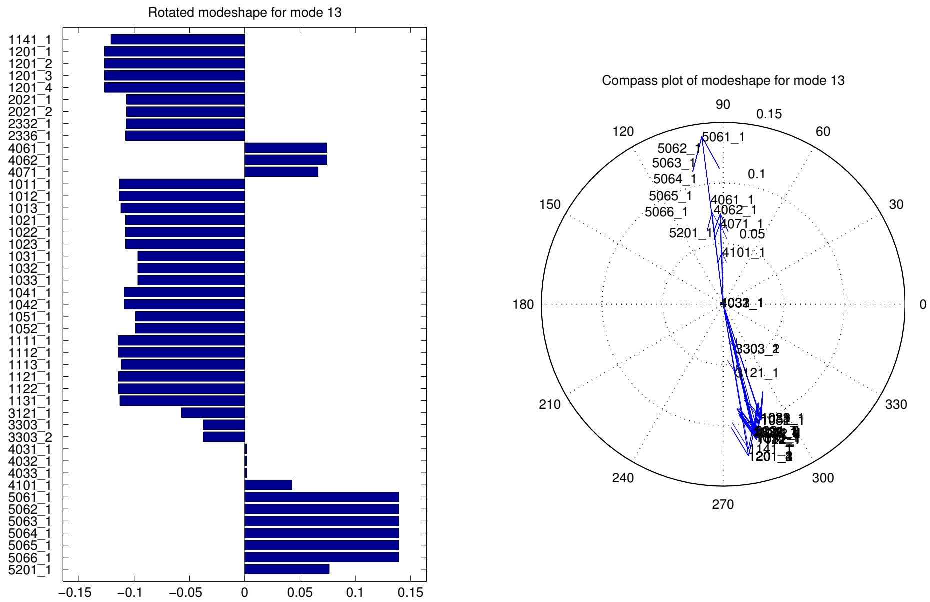

Figure 6.16: The mode shape for mode 13

By looking at the results of the modal analysis without the existing PSS's a different behavior is seen. Some modes have disappeared and some not. This implies that tuning of PSS's can affect modes detrimentally if not tuned right. The same power plants seem to be the key players as before. That is Hrauneyjar, Vatnsfell, Kárahnjúkar, Krafla and Blanda. These power plants except Vatnsfell all have a PSS in the original model. A damping strategy for the system with PSS's in those places will therefore be designed.

Chapter 7

Selecting PSS and location

In the previous chapter a strategy to add sufficient damping to the Icelandic power system was proposed. The following sections aim at selecting a PSS model to use in verification of the damping strategy as well as verifying that placement of a PSS at the suggested locations has desired effect.

7.1 Selecting PSS model

In order to verify that damping can be improved it should be straightforward to use the PSS1A model from chapter 4. This model is easily implemented and can be tuned without difficulties. Although it has been shown that this model is sensitive to power ramping and torsional disturbances in real situations it is nevertheless valid in verifying that damping can be increased.

The in signals that can be used as inputs to the PSS can be rotor speed, active power or bus frequency. A $\Delta\omega$ input PSS is directly linked to theory so it seems logical to choose that signal as input to all PSS. In reality a PSS solution for each plant should be tailored specifically to its characteristics.

7.2 Location verification

In order to verify that PSS's at the suggested locations from chapter 6 have the desired effect, participation factors and residues can be used. By analyzing speed participation factors for each generator in each mode it can be seen how much participation a certain generator has in a mode. If the participation of a generator is low it is likely that placement of a PSS there should not have the desired effect. The speed participation factor therefore gives a sensitivity estimate on how much the damping of a mode is affected by feedback through a PSS.

A residue is the multiple of controllability and observability. By calculating the controllability of all modes from the V_{ref} input of AVR's in the system it can be seen whether the modes are controllable from these inputs. If $\Delta\omega$ is not observable from the modes, a PSS with that signal as input will not affect the mode. The residues therefore give an estimate on the sensitivity of a mode to feedback through a PSS. If the residue is 0, either controllability or observability is zero meaning that the PSS will have no effect. These two estimates therefore give an indication whether a location of a PSS has desired effect [2].

The speed participation factors and residues for the modes with less than 5% damping observed in case 0 without existing PSS's can be viewed in figures 7.1 to 7.9. From figure 7.1 and 7.2 it can be seen that placement of a PSS at Vatnsfell should be able to add damping to the local modes there. The same can be said about damping of local modes at Hrauneyjar by looking at figures 7.3 and 7.4.

By looking at figure 7.5 it can be seen that Laxá has the biggest participation and residue. This power plant on the other hand is considerably smaller than Blanda and therefore it is not likely that a PSS would have any effect there. The participation and residues for Blanda are not zero so a PSS at Blanda should be able to add damping to this mode.

Mode 8 is where Hrauneyjar and Vatnsfell oscillate against other generators in the 220 kV network. The participation factors for these plants in this modes are the highest and the residues are not zero. Therefore placement of PSS's at these locations aught to add damping to this mode. Mode 9 is essentially Blanda oscillating against Krafla. By looking at figure 7.7 it can be seen that the participation factors for these plants are high in this mode but the residues for Krafla are significantly lower than at Blanda. It indicates that a placement of a PSS at Blanda should have more effect than at Krafla. The placement of a PSS at Krafla on the other hand should not do any harm. The same can be said about mode 12 where Krafla and Blanda oscillate against the rest of the system.

Figure 7.9 displays the participation and residues for the inter area mode. It can be seen from this figure that placing a PSS at Kárhnjúkar should be able to add damping to this mode. It should also help in damping this mode to place a PSS at Hrauneyjar.

From the analysis of participation factors and residues it can determined that placing correctly tuned PSS's at Hrauneyjar, Vatnsfell, Kárahnjúkar, Blanda and Krafla should be able to improve damping in the system. By using participation factors and residues, locations for PSS's can be screened. There is however no guarantee for that they will work, as modes can affect each other [15].

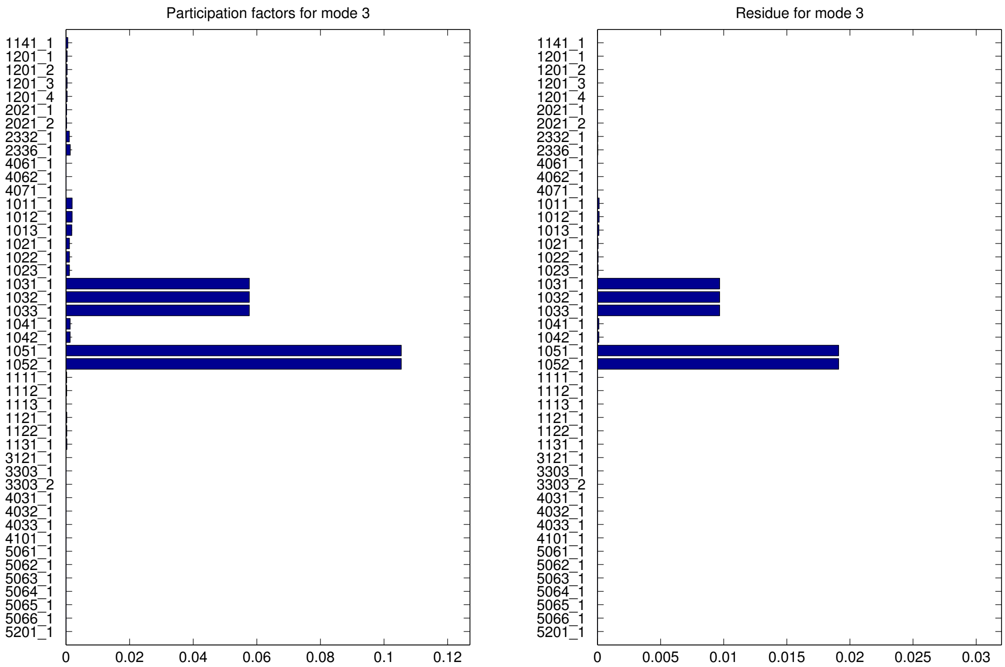

Figure 7.1: Speed participation factors and residues for mode 3

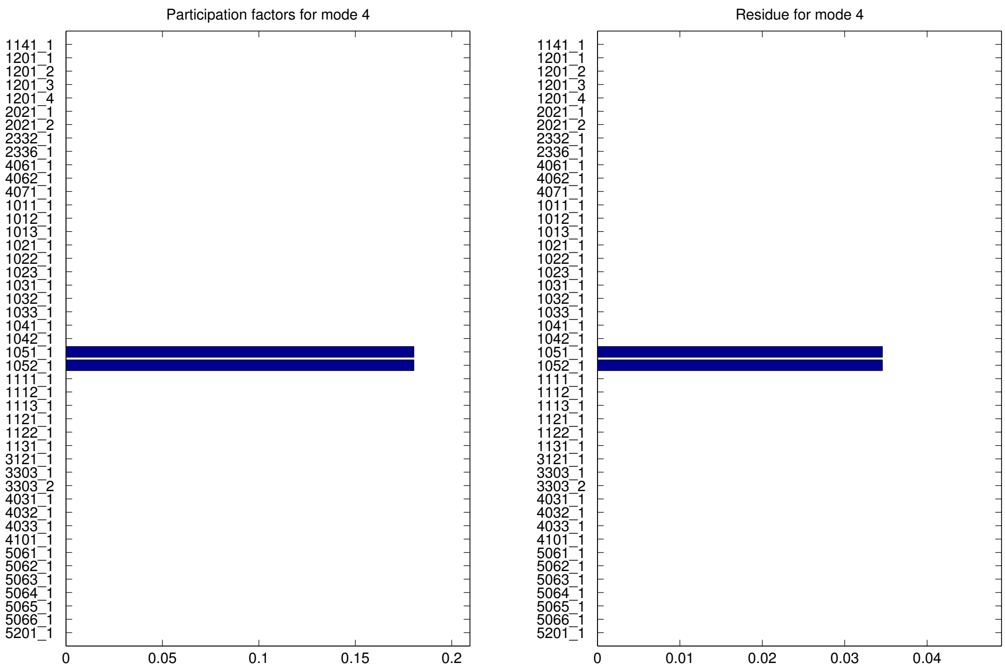

Figure 7.2: Speed participation factors and residues for mode 4

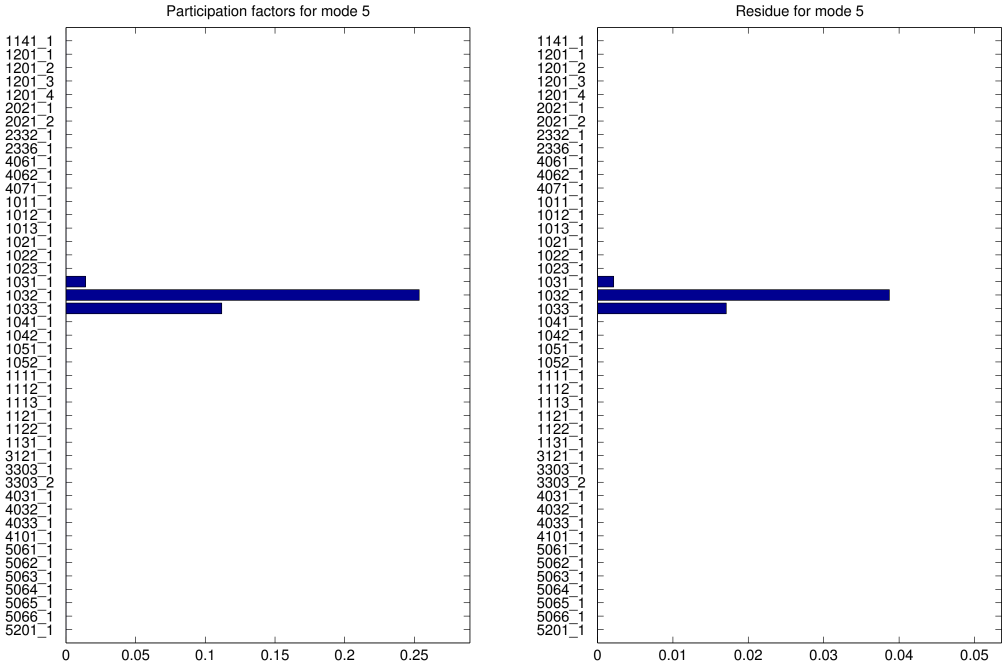

Figure 7.3: Speed participation factors and residues for mode 5

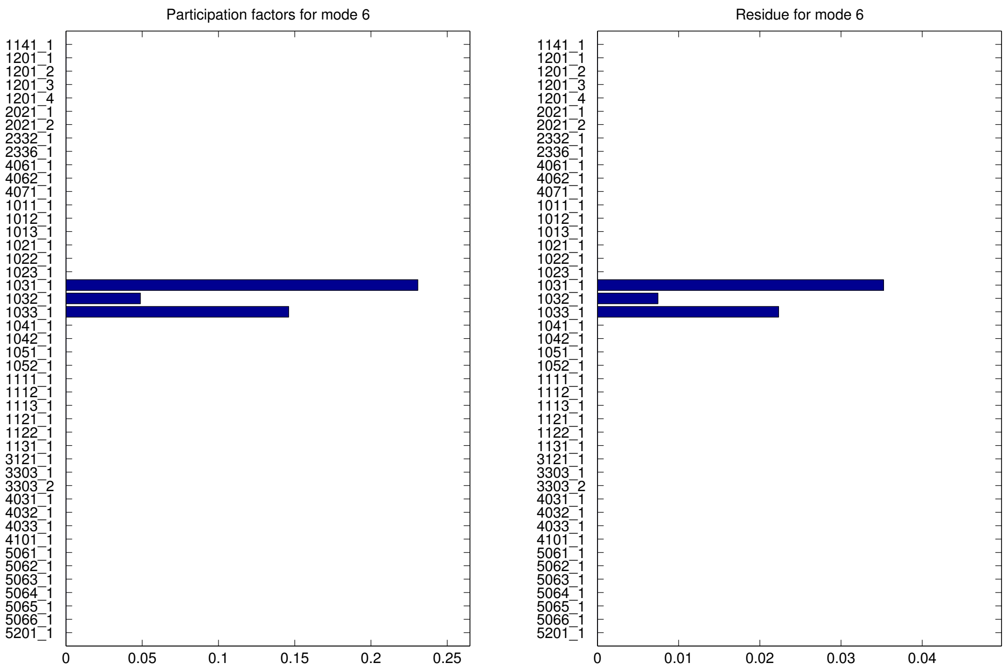

Figure 7.4: Speed participation factors and residues for mode 6

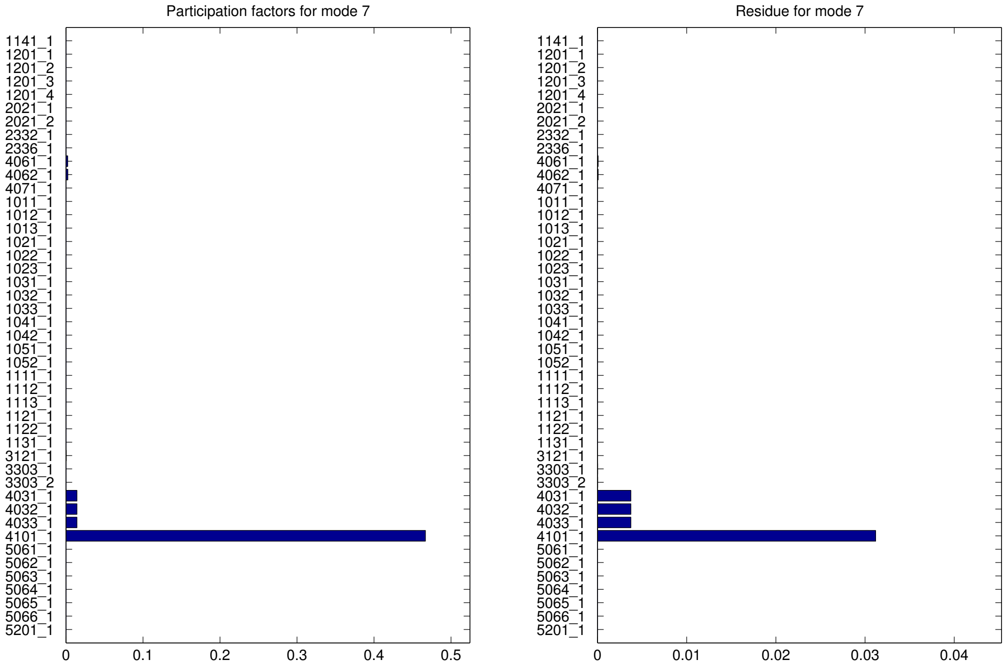

Figure 7.5: Speed participation factors and residues for mode 7

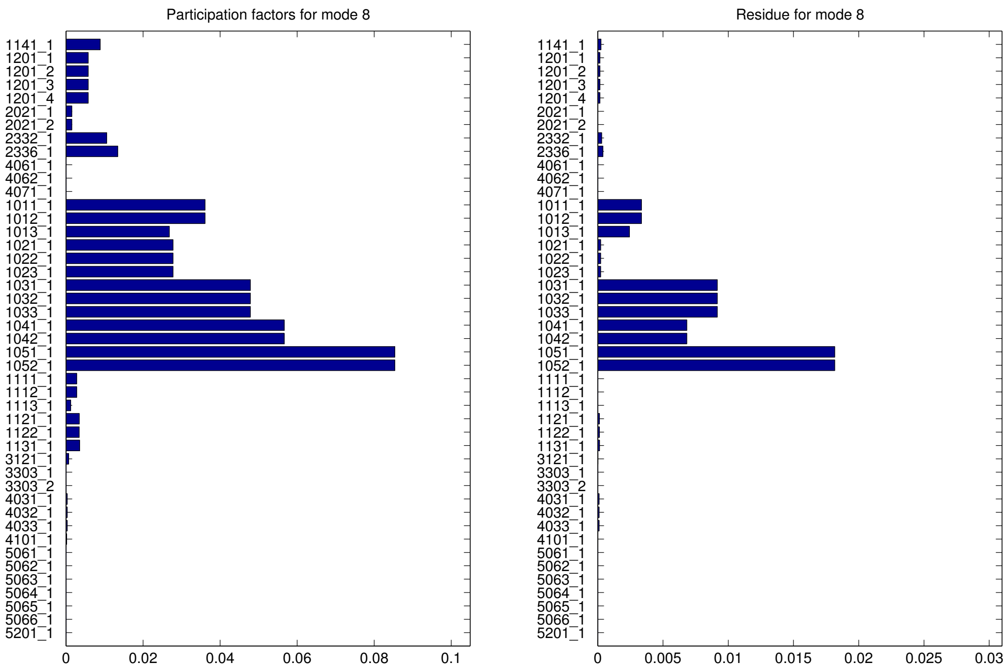

Figure 7.6: Speed participation factors and residues for mode 8

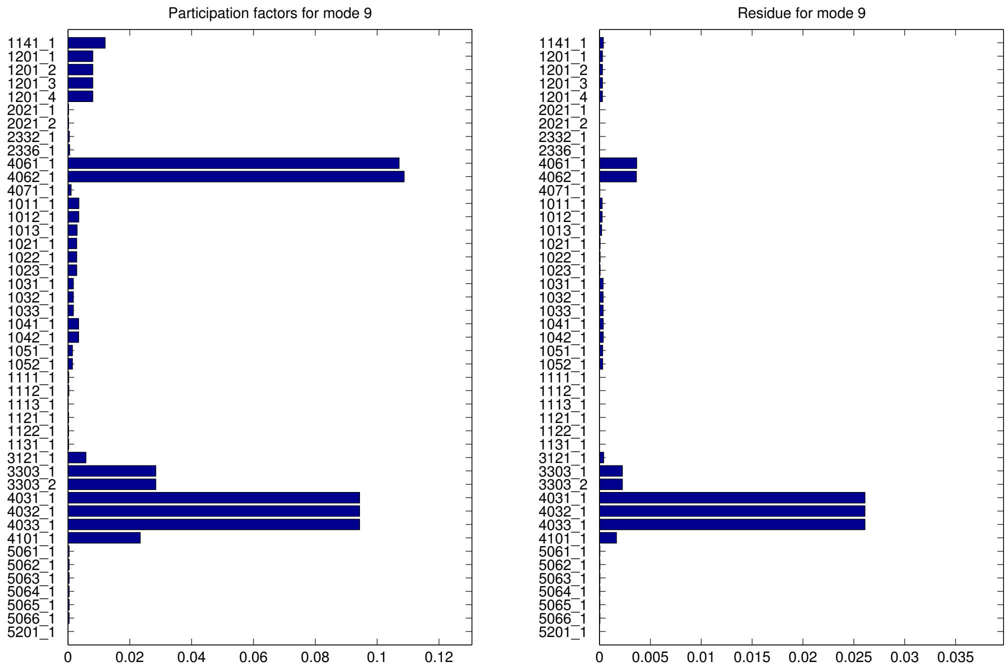

Figure 7.7: Speed participation factors and residues for mode 9

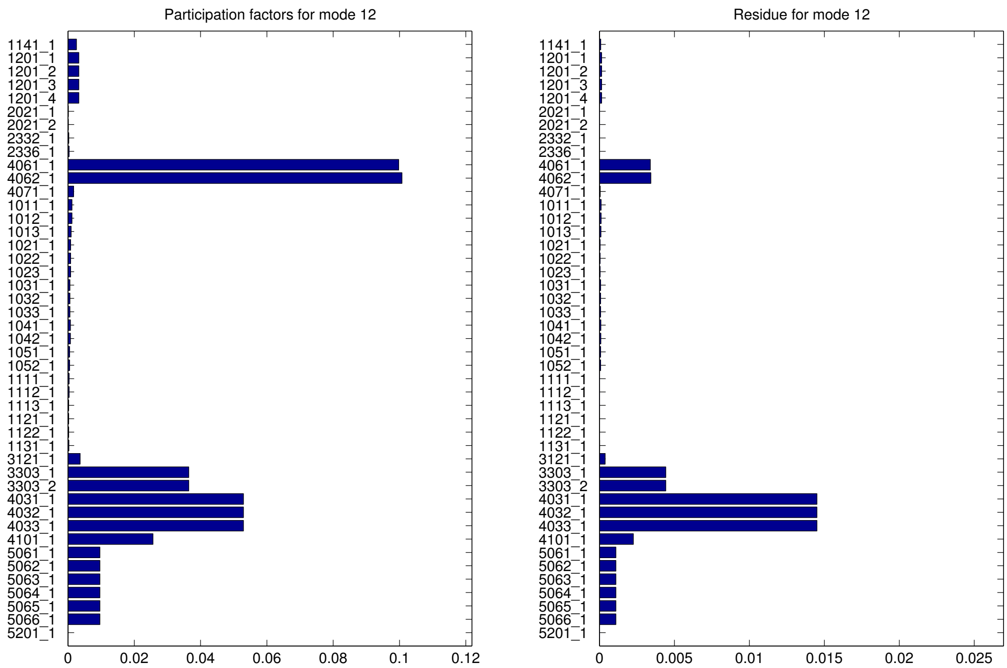

Figure 7.8: Speed participation factors and residues for mode 12

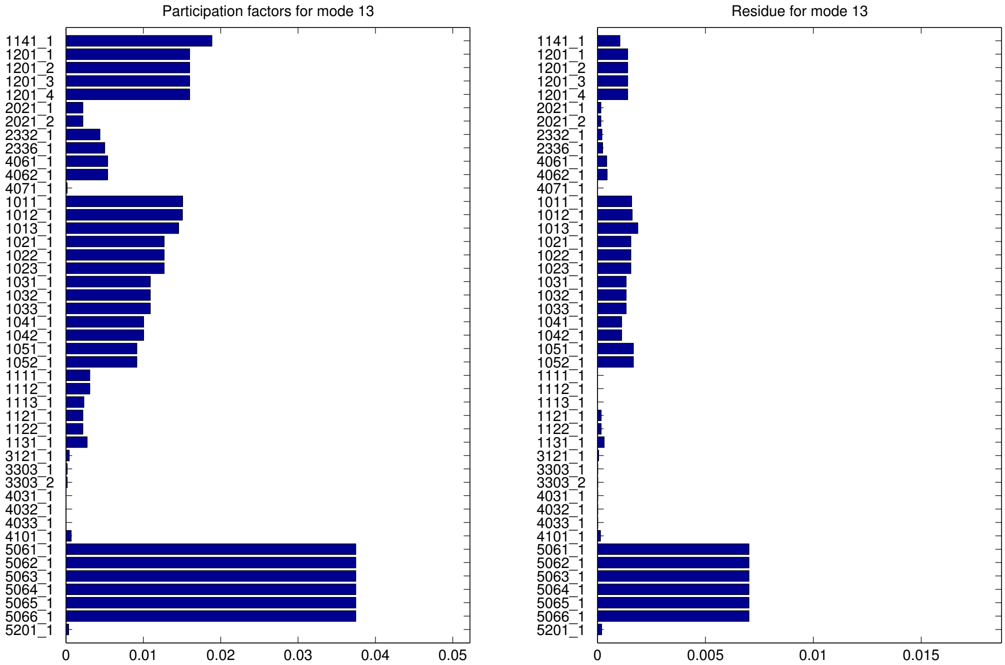

Figure 7.9: Speed participation factors and residues for mode 13

Chapter 8

PSS tuning

In order to implement the damping strategy proposed, a PSS has to be specifically tuned for each location. This chapter describes the methods used to match phase characteristics, search for suitable gain and the results of implementing the damping strategy in the system.

8.1 Methods

As has been stated before, the basic principle behind a PSS is to add a modulating signal to the input of an AVR in order to introduce electrical torque damping component. In order to accomplish this the PSS has to compensate for the phase shift caused by the AVR, generator and power system. The most common method is to use two lead-lag filters. This is the method used in the PSS1A model.

A filter made up of two lead-lag filters is represented by equation 8.1.

$$F(s) = \frac{1 + T_1 s}{1 + T_2 s} \frac{1 + T_3 s}{1 + T_4 s} \tag{8.1}$$

In order to match the phase of the lead-lag filters the four time constants have to be adjusted. This can be done manually as well as automatically. Adjusting the constants by hand in order to find a good phase match is considered tedious.

In [16] it has been pr oven that a slightly modified least squares solution can be used to determine the parameters of the ratio of polynomials with good results. The only drawback is that there is no control over the range of parameters to be estimated. In the optimization toolbox of *Matlab* there is a function called *lsqcurvefit* which can solve a nonlinear least squares problem where boundaries can be set on parameters. This is the basis for the method that will be used for the phase curve fitting [14], better describe in appendix A.

The phase characteristics to match by a PSS can be derived from a linearized ODE model of a power system. This is done by removing the columns and rows corresponding to angles and speeds of the generators, that is the angles ($\Delta\delta$) and the speeds ($\Delta\omega$) are kept constant [2]. In this way a transfer function on the form of 8.2 can be derived.

$$\frac{Y(s)}{U(s)} = C_{ode}(sI - A_{ode})^{-1}B_{ode} + D_{ode} \tag{8.2}$$

By choosing the output signal as $\Delta\omega$ and the input signal as V_{ref} it is therefore possible to derive a transfer function of the form of equation 8.3 which is exactly the reverse of characteristics the lead-lag filters have to compensate for.

$$G(s) = \frac{\Delta\omega}{V_{ref}} \tag{8.3}$$

8.2 Phase fitting

The results of the phase compensation can be viewed in the following sections. In all of the cases a washout filter constant of $T_w = 10$ s has been chosen. All comparison of phases include the washout filter.

To display the results a bode diagram of the gain and phase of the corresponding PSS is shown. The phase matching is most important as the PSS has to compensate for the phase deviation from the input V_{ref} to $\Delta\omega$ in order to be able to add damping in the frequency range of oscillations. To establish that the phase matching has succeeded, a bode diagram of the gain and phase of the feedback signal path from $\Delta\omega$ to ΔT_e is displayed also.

In [1] it is stated that when adjusting the compensating phase of a PSS it is a good rule to always try to have a little under compensation. In this way it is possible to make up for uncertainties in modeling. The following therefore displays results of phase matching with a slight under compensation.

8.2.1 Hrauneyjar

The compensation function of the PSS is:

$$G(s) = \frac{1 + 0.1344s}{1 + 0.0100s} \frac{1 + 0.1344s}{1 + 0.0100s}$$

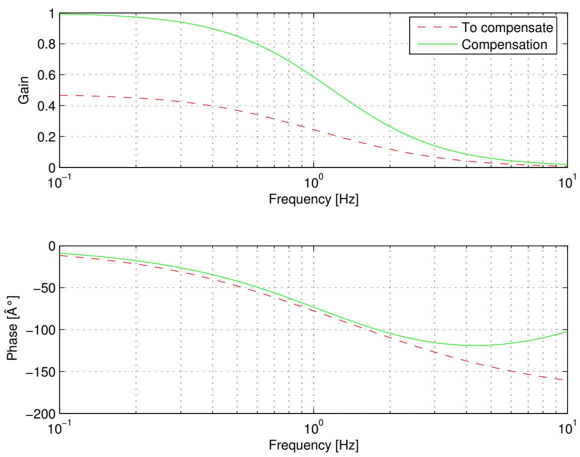

Figure 8.1: Compensation by PSS at Hrauneyjar with washout filter

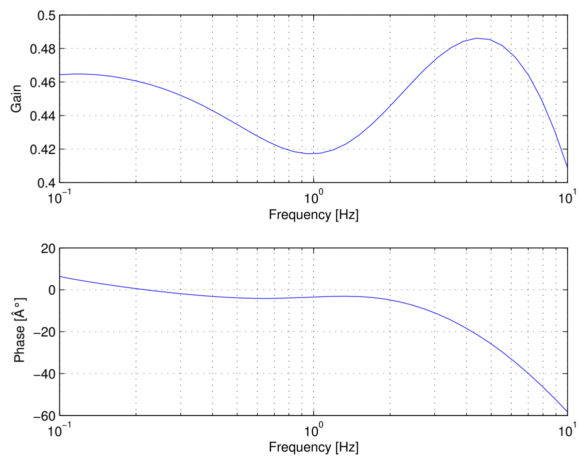

Figure 8.2: Phase of the feedback signal path at Hrauneyjar

8.2.2 Vatnsfell

The compensation function of the PSS is:

$$G(s) = \frac{1 + 0.1524s}{1 + 0.0130s} \frac{1 + 0.1524s}{1 + 0.0130s}$$

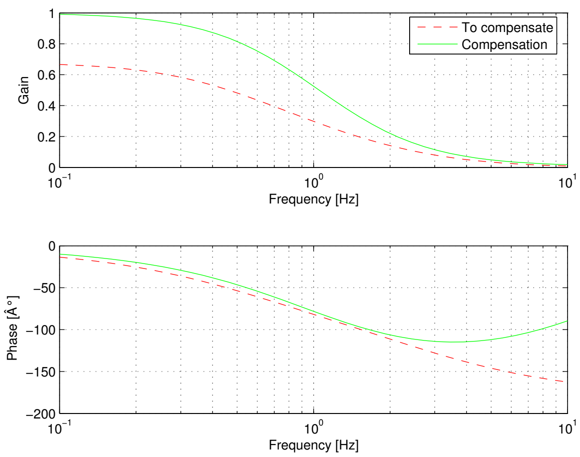

Figure 8.3: Compensation by PSS at Vatnsfell with washout filter

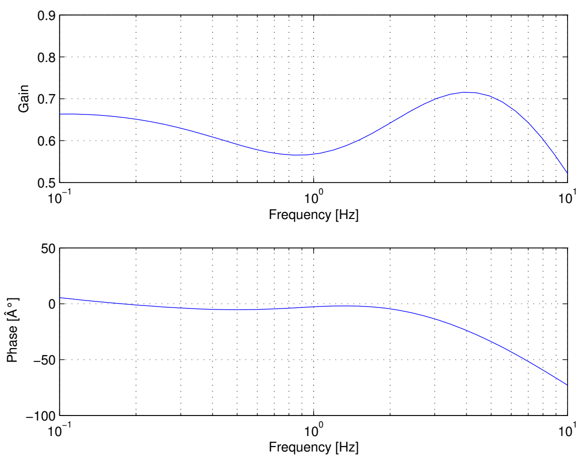

Figure 8.4: Phase of the feedback signal path at Vatnsfell

8.2.3 Kárahnjúkar

The compensation function of the PSS is:

$$G(s) = \frac{1 + 0.4097s}{1 + 0.0404s} \frac{1 + 0.4097s}{1 + 0.0404s}$$

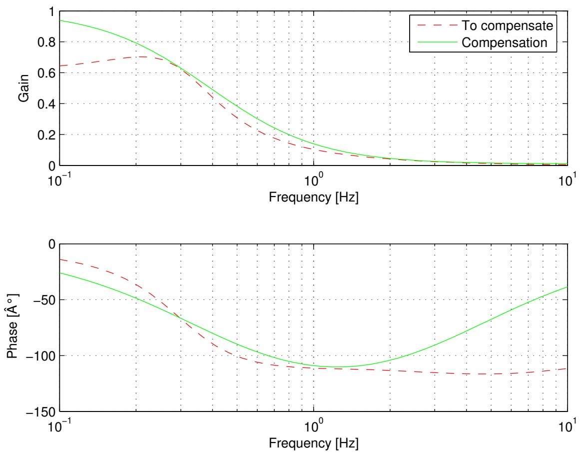

Figure 8.5: Compensation by PSS at Kárahnjúkar with washout filter

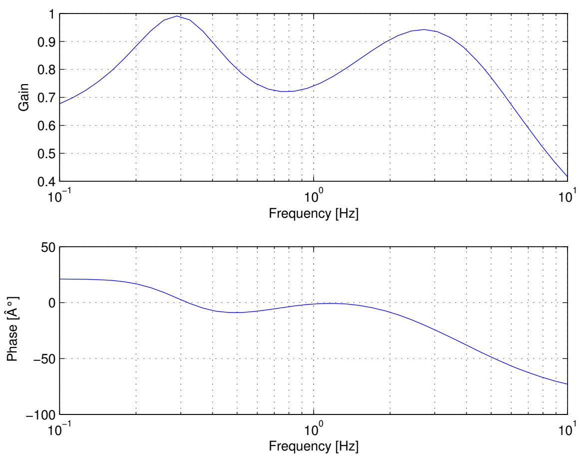

Figure 8.6: Phase of the feedback signal path at Kárahnjúkar

8.2.4 Krafla

The compensation function of the PSS is:

$$G(s) = \frac{1 + 0.7933s}{1 + 0.0100s}\frac{1 + 0.7933s}{1 + 0.0100s}$$

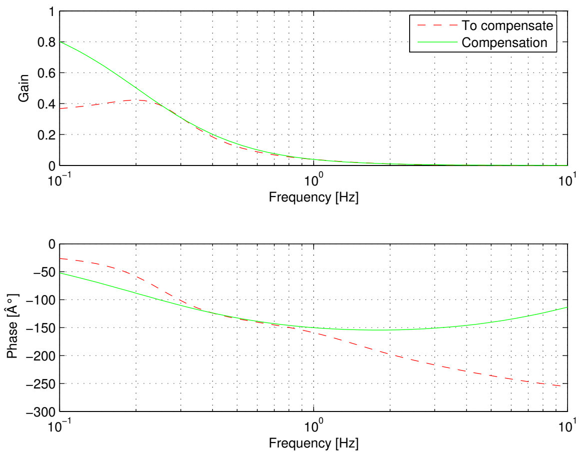

Figure 8.7: Compensation by PSS at Krafla with washout filter

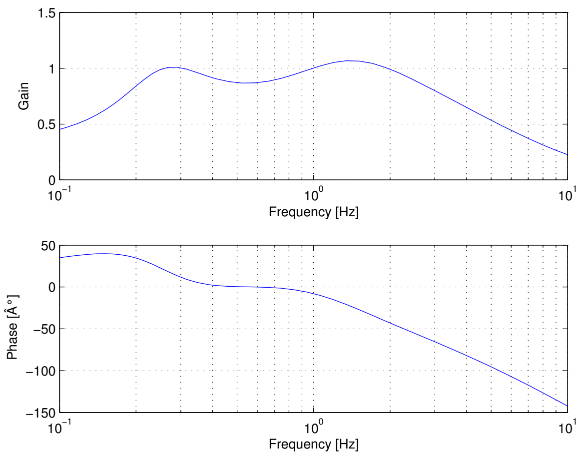

Figure 8.8: Phase of the feedback signal path at Krafla

8.2.5 Blanda

The compensation function of the PSS is:

$$G(s) = \frac{1 + 0.1906s}{1 + 0.0100s}\frac{1 + 0.1906s}{1 + 0.0100s}$$

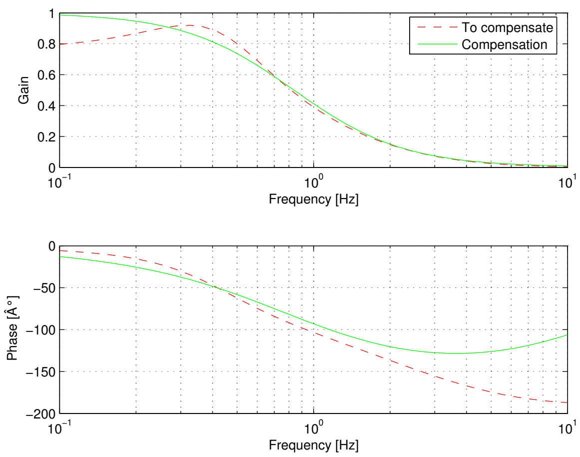

Figure 8.9: Compensation by PSS at Blanda with washout filter

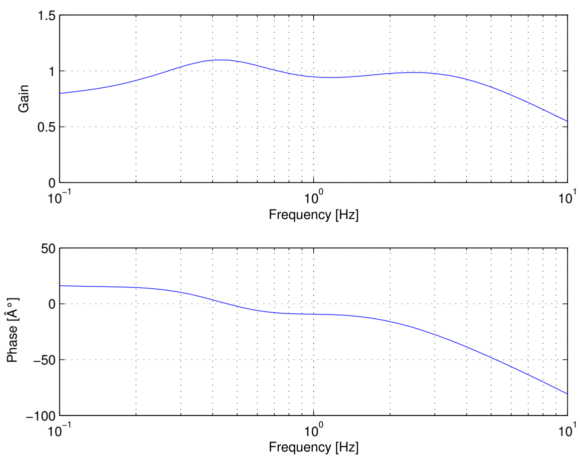

Figure 8.10: Phase of the feedback signal path at Blanda

8.2.6 Comparison

A comparison of the parameters of the PSS's can be viewed in table 8.1. As can be seen there is no such thing as default PSS parameters. All parameter sets vary between locations.

Parameters	Hrauneyjar	Vatnsfell	Kárahnjúkar	Krafla	Blanda
T_1	0.1344	0.1524	0.4097	0.7933	0.1906
T_2	0.0100	0.0130	0.0404	0.0100	0.0100
T_3	0.1344	0.1524	0.4097	0.7933	0.1906
T_4	0.0100	0.0130	0.0404	0.0100	0.0100

Table 8.1: PSS parameters for all locations

By looking at the bode diagrams for the PSS's at Hrauneyjar and Vatnsfell in figures 8.1 and 8.3 it can be seen that the phase characteristics are very well matched over the frequency range of oscillations. This can also be seen from the phase diagrams of the signal paths in 8.2 and 8.4. These PSS's should therefore be able to add good damping to the modes, these two plants take part in.

Phase compensation of the PSS's at Kárahnjúkar is more difficult to attain than in the previous cases as can be seen in 8.5. But nevertheless it matches the frequency range of oscillations pretty well and the phase of the signal path is almost zero, as seen in 8.6

The phase compensation of the PSS at Krafla is the most difficult phase matching to be obtained. It matches lower frequencies quite well but is a little bit to much under compensated at higher frequencies. But nevertheless the overall match is all right.

Finally the compensation of the PSS at Blanda is pretty good. It follows the characteristic fairly well and therefore the Blanda PSS should be able to add good damping.

8.3 Selecting gain

The root locus plots aid in selecting the gain of the PSS. When gain is increased in some PSS's it could have detrimental effect on control modes related to the AVR. Therefore care has to be taken while choosing gain. All plots show when the gain is varied from 0 to 30 in steps of 5. By looking at the plots it can be seen how the poles travel towards the zeros when the gain is increased. If a pole and a zero coincide it means that the corresponding mode is uncontrollable and unobservable. The inter area mode is the mode that is closest to the origin of the root locus plot for a gain of zero.

8.3.1 Hrauneyjar

The gain can be increased from 0 to 30 without large destabilization of any mode. In order to reach sufficient damping a minimum gain of approximately 10 should be needed. A gain of 20 should be sufficient.

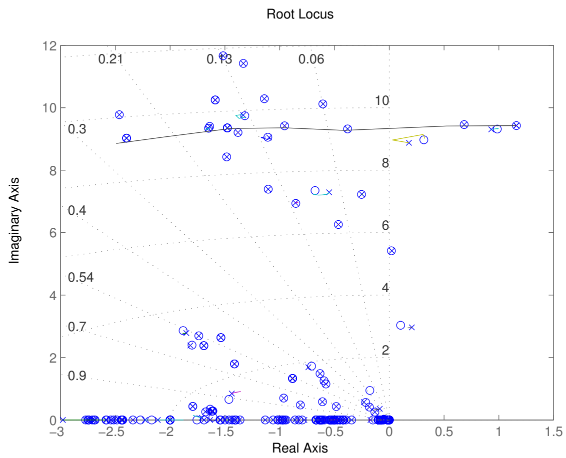

Figure 8.11: Root locus for the PSS at Hrauneyjar

8.3.2 Vatnsfell

The gain can be increased from 0 to 30 without large destabilization of any mode. In order to reach sufficient damping a minimum gain of approximately 10 should be needed. A gain of 20 should be sufficient.

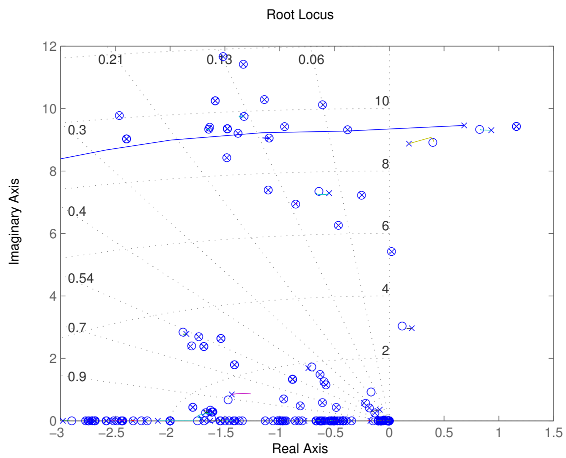

Figure 8.12: Root locus for the PSS at Vatnsfell

8.3.3 Kárahnjúkar

The gain can be increased from 0 to 30 without large destabilization of any mode. In order to reach sufficient damping a minimum gain of approximately 10 should be needed, to avoid any more destabilization of the modes that lie in the middle almost at the bottom of the plot a gain of more than 30 should be avoided. A gain of 20 should be sufficient.

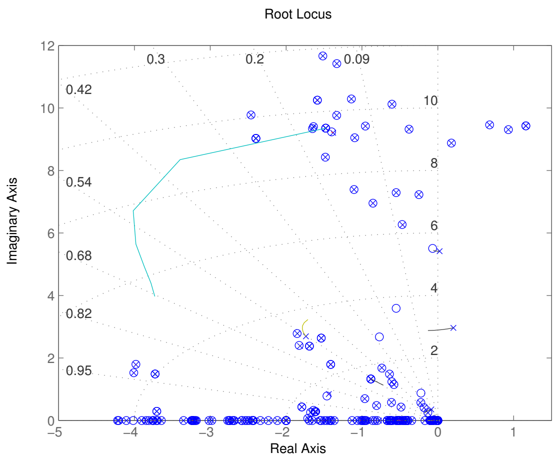

Figure 8.13: Root locus for the PSS at Kárhnjúkar

8.3.4 Krafla

The gain can be increased from 0 to 30 without large destabilization of any mode. In order to reach sufficient damping a minimum gain of approximately 5 should be needed. As can be seen from the plot damping of some modes increases and then decreases again, so a gain of more than 10 should be avoided. A gain of 5 should be sufficient.

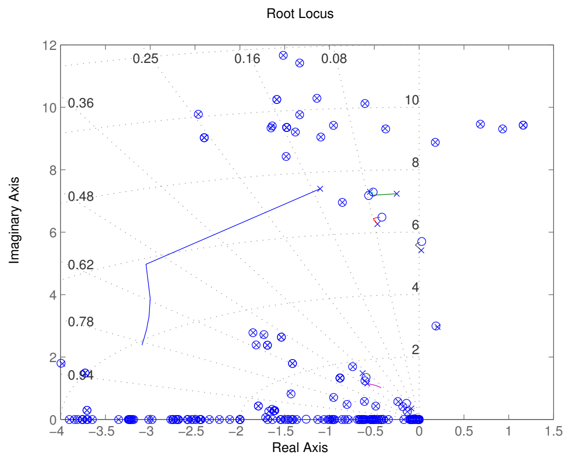

Figure 8.14: Root locus for Krafla

8.3.5 Blanda

The gain can be increased from 0 to 30 without large destabilization of any mode. In order to reach sufficient damping a minimum gain of approximately 5 should be needed. As can be seen there is one mode in the bottom of the plot at the middle that is destabilized somewhat. In order not to cause any more destabilization, a gain of more than 20 should be avoided. A gain of 10 should be sufficient.

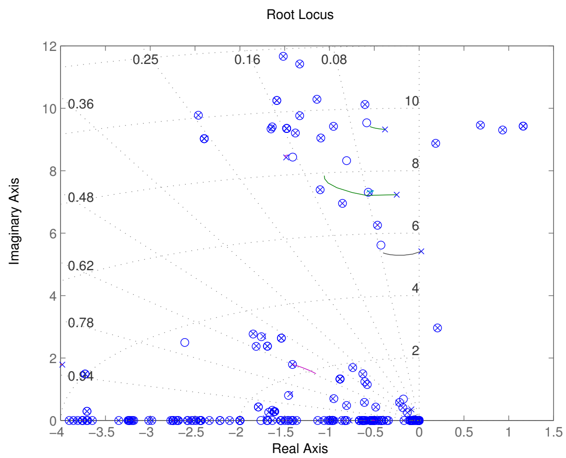

Figure 8.15: Root locus for Blanda

8.3.6 Results

By setting the gain of Hrauneyjar, Vatnsfell and Kárhnjúkar to 20, Blanda to 10 and Krafla to 5 all modes get better damping than 6%. In figures 8.16 to 8.18 the eigenvalues for the state matrix A_{ode}, for each of the cases 0-2, can be viewed. They confirm that all modes have better than 6% damping. This means that the 5% requirement and the NORDEL requirement are met for all modes in all test cases, which can be considered quite good. It can also be seen that the majority of modes even have better damping than 10%.

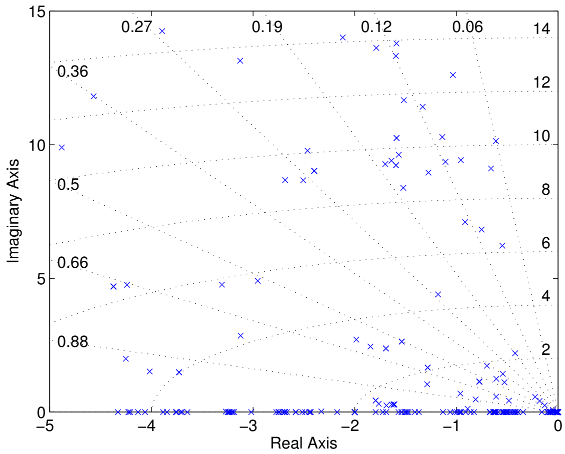

Figure 8.16: Case 0: Eigenvalues of A_{ode} with new PSS strategy

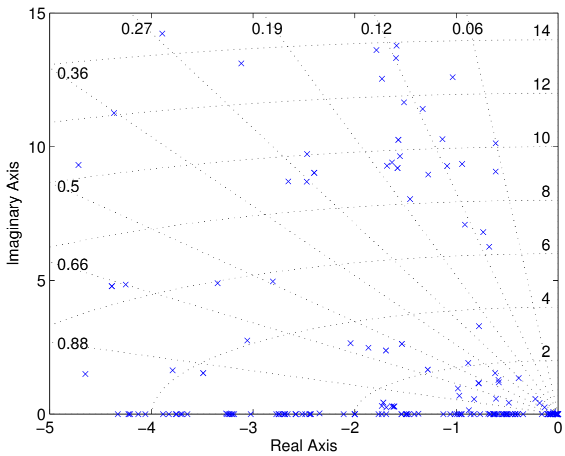

Figure 8.17: Case 1: Eigenvalues of A_{ode} with new PSS strategy

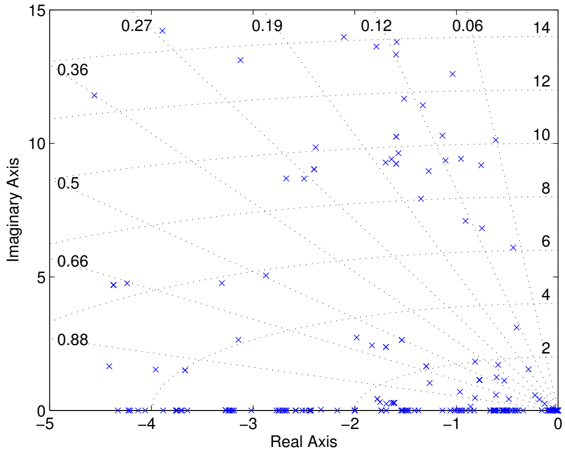

Figure 8.18: Case 2: Eigenvalues of A_{ode} with new PSS strategy

Chapter 9

Time simulations

Up to this point, the focus of this thesis has been on analyzing small signal stability based on linear models and coming up with a strategy to improve damping in a power system. The original model of the power system is nonlinear. In order to verify that the damping strategy based on a linearized version of this model apply, time simulations are necessary. This chapter reveals results of time simulations on the Icelandic power system with the original setup of PSS's and the damping strategy devised in chapter 8.

9.1 Remarks

By looking at the results of time simulations for all cases it can be seen that damping is increased significantly in case 0 and case 2. However in case 1 there is loss of synchronism in both cases. After installing the re tuned PSS's it seems that the loss of synchronism is delayed somewhat. The loss of synchronism can not be improved by installing PSS's. To prevent loss of synchronism, synchronizing torque has to be improved.

9.2 Case 0

This case is less severe than the other cases so less difference may be noted between damping before and after retuning. Also the oscillations are not very big. It can be seen that constant oscillations at Hrauneyjar and Vatnsfell are entirely damped. The oscillation at Blanda is slightly better damped than before. The damping of the oscillation at Krafla is around the same. Finally the small oscillation at Kárahnjúkar is damped. The outputs of the PSS's can be viewed in figure 9.2. They are well under the 5% limiting in all cases except Blanda and Krafla where the signal hits the limit slightly in the case of Blanda and more for Krafla.

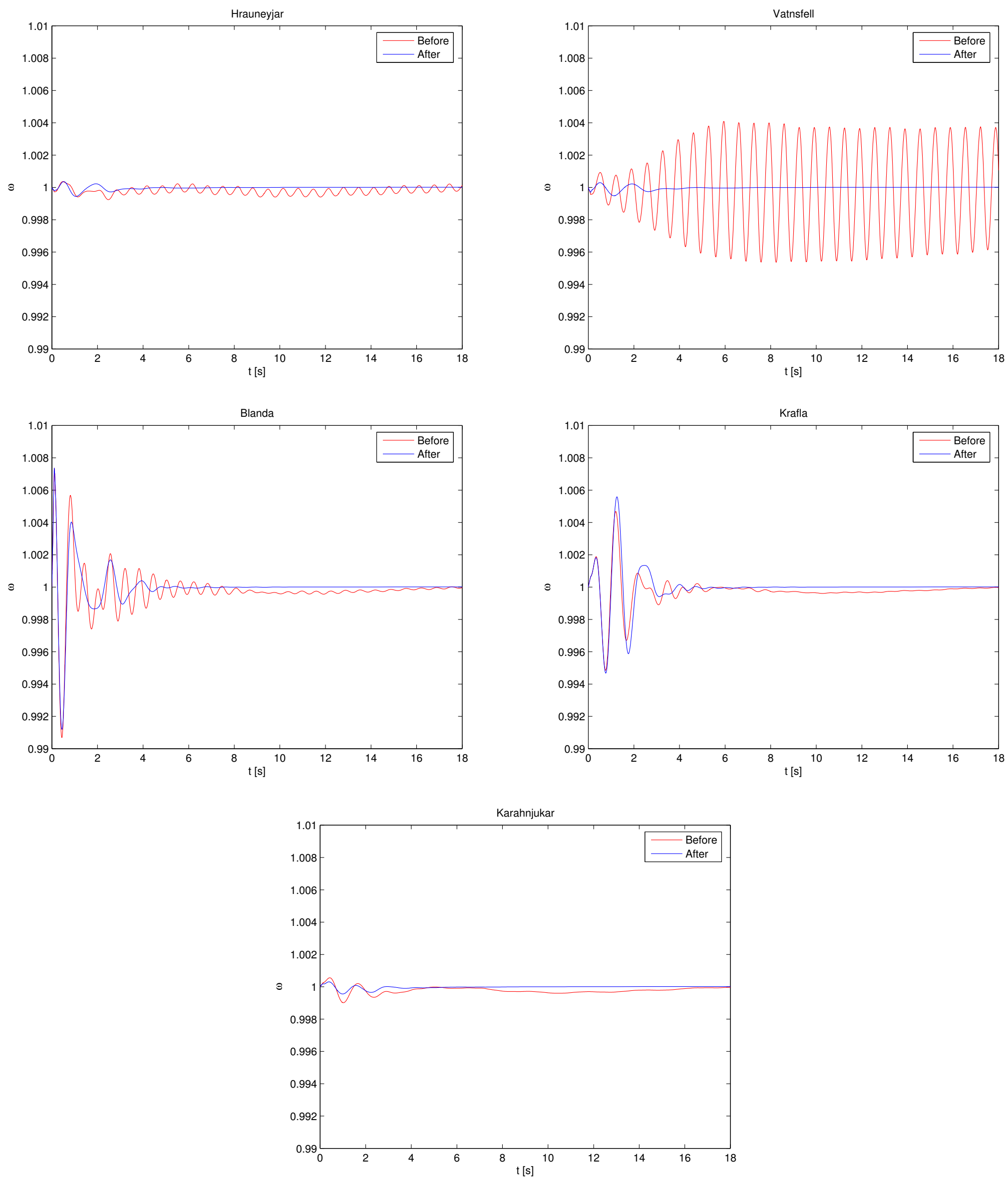

Figure 9.1: Case 0: Rotor speeds at PSS location before and after tuning

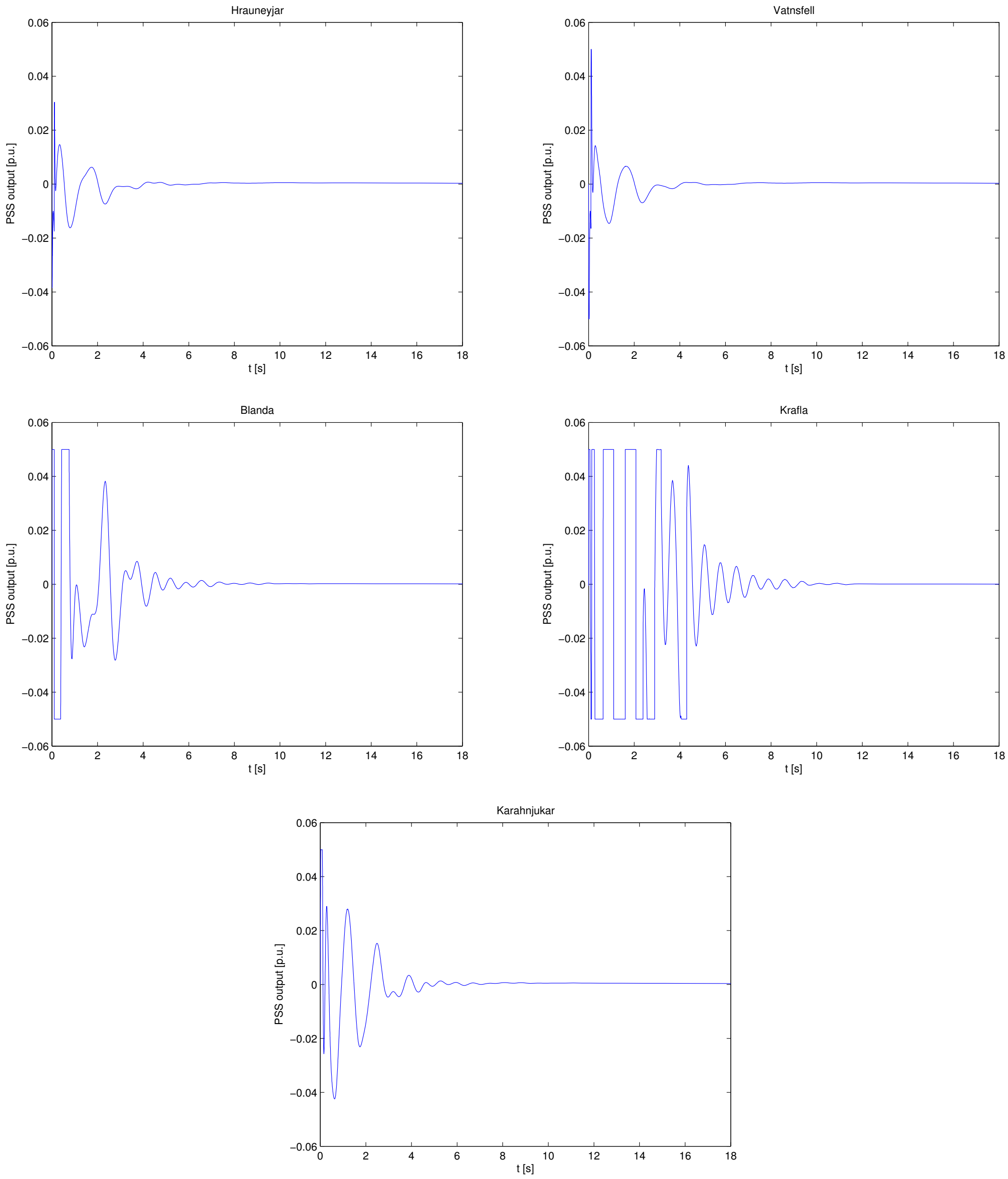

Figure 9.2: Case 0: Outputs of PSS's after tuning

9.3 Case 1

This case is pretty severe as synchronism is lost, both before and after. Therefore the results can't be compared. In order to keep the system in synchronism, synchronizing torque has to be added which is not possible via PSS. The output signals of the PSS's can be seen in figure 9.4.

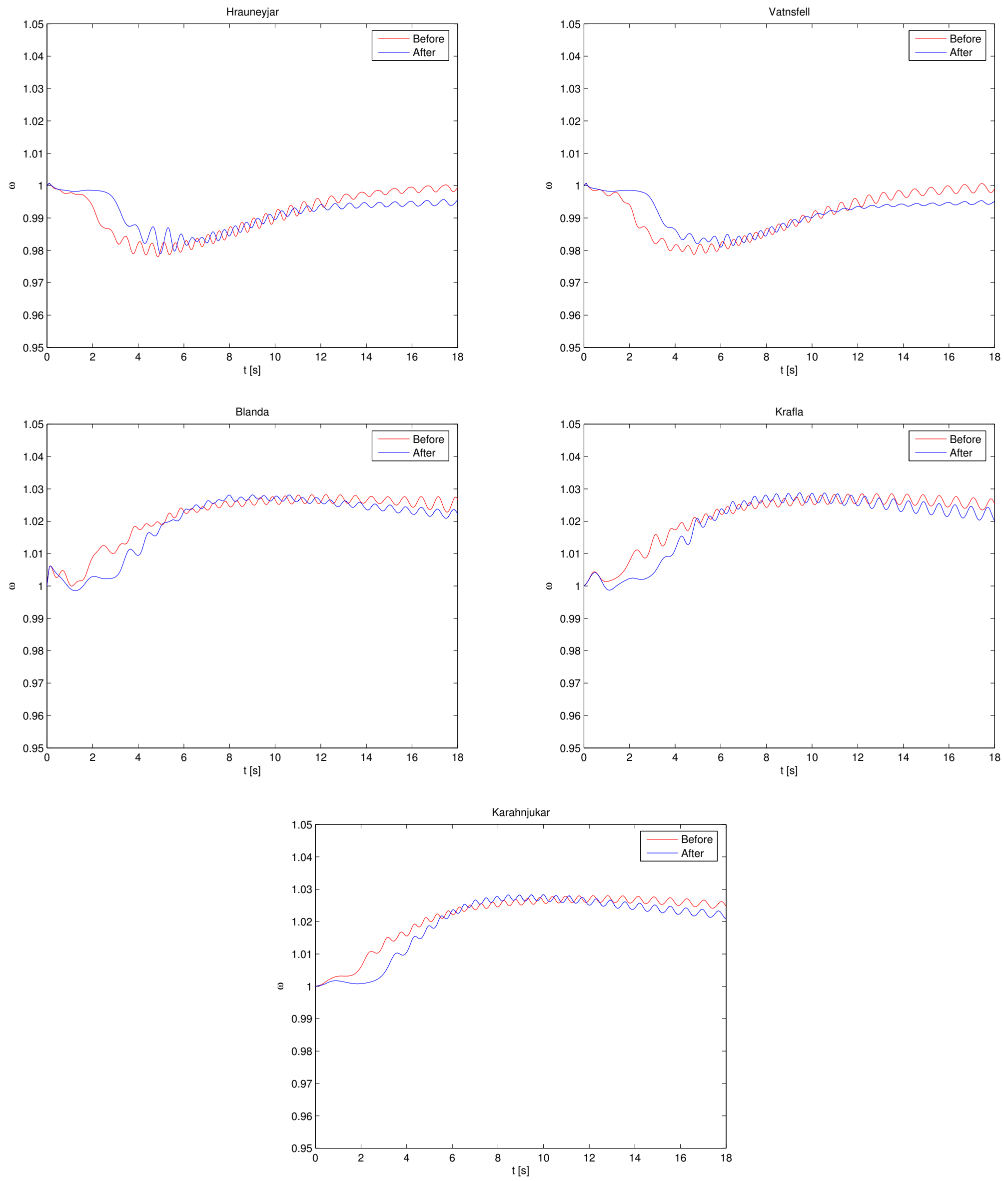

Figure 9.3: Case 1: Rotor speeds at PSS location before and after tuning

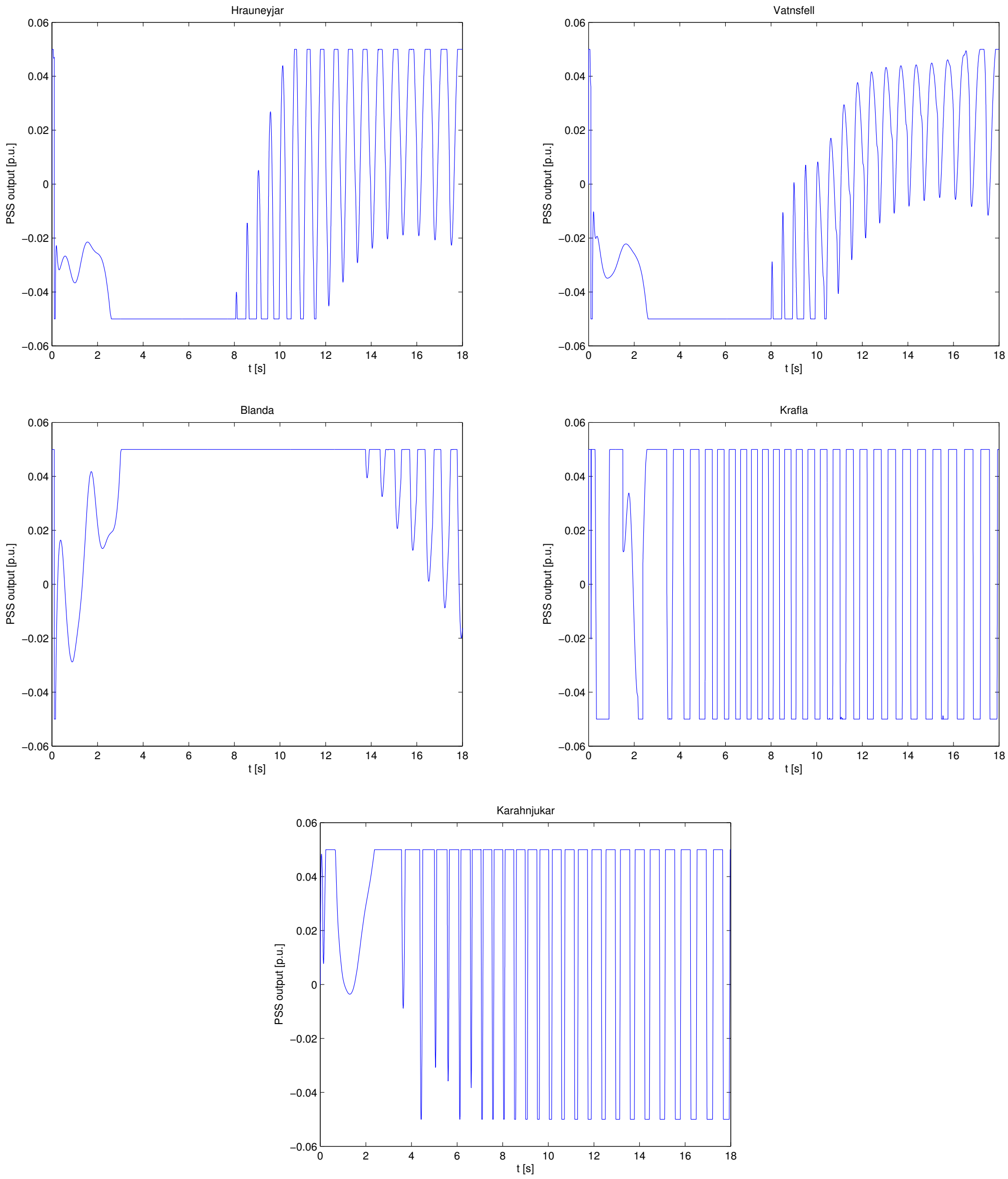

Figure 9.4: Case 1: Outputs of PSS's after tuning

9.4 Case 2

This case shows the direct benefits of retuning. Before, oscillations at all locations are growing. But after the retuning all oscillations are damped in around 6 s. The output signals of the PSS's can be viewed in figure 9.6. As can be seen from this figure the outputs of the PSS's are well inside the 5% limiting except for Krafla which as before hits the limits but a little less than in case 1.

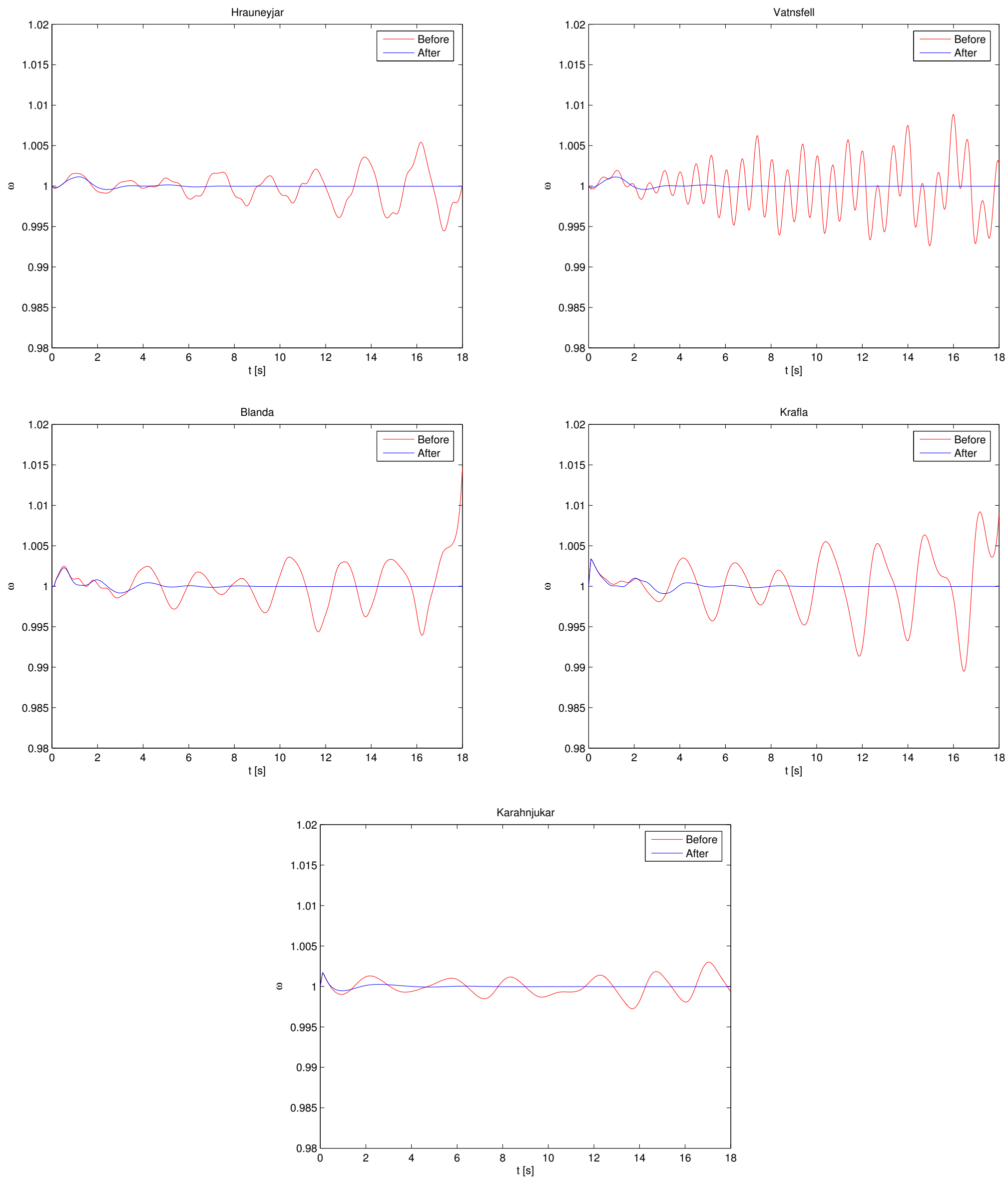

Figure 9.5: Case 2: Rotor speeds at PSS location before and after tuning

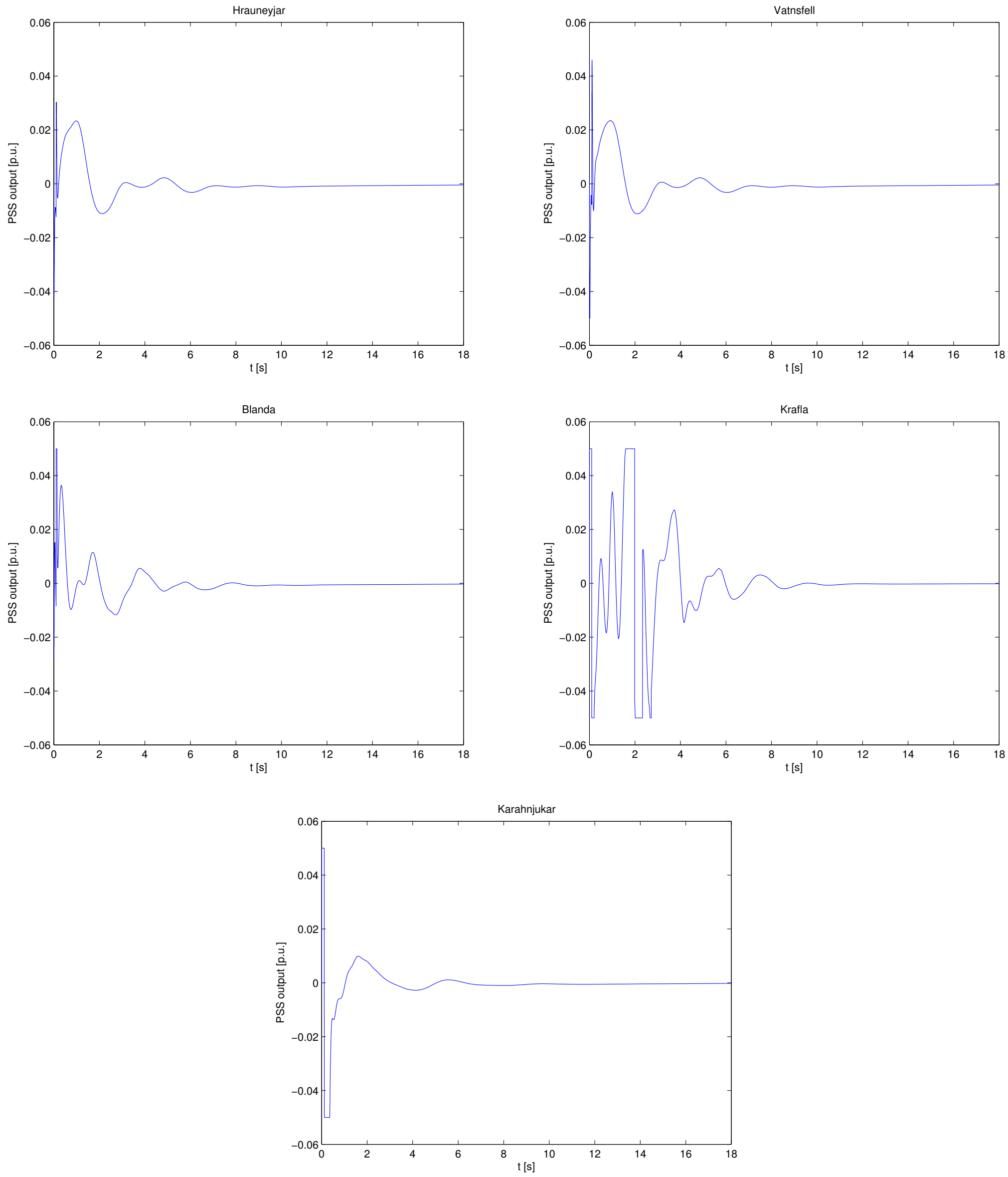

Figure 9.6: Case 2: Outputs of PSS's after tuning

9.5 On loss of synchronism

From time simulations of case 1 it can be seen that there is loss of synchronism. This means that the N-1 criteria is lost in this case. In order to investigate this post fault line flow can be checked on the following lines:

- WEST: Brennimelur - Vatnshamrar
- NW: Hrútatunga - Laxárvatn
- N: Varmahlíð- Rangárvellir
- NE: Krafla - Fljótsdalur
- E: Hryggstekkur - Teigarhorn
- SE: Hólar - Prestbakki
- SE: Prestbakki - Sigalda

In table 9.1 the post fault line flows for each case can be viewed. From the column with line flows in case 1 it can be seen that the line flow on all lines except NW is more than twice the load flow for case 0. This could be an indication as to why synchronism is lost.

Line flow (MVA)	Case 0	Case 1	Case 2
WEST	50.0899	0	64.2153
NW	97.9018	56.7631	112.5028
N	9.3606	57.2701	8.9454
NE	18.6454	64.8140	0
E	56.3494	95.7265	39.5835
SE	35.4911	66.4037	23.0228
S	31.8159	62.1717	17.3003

Table 9.1: Post fault line flow for case 0-2

Chapter 10

Further work

Before implementing a damping strategy such has the one that has been designed in this thesis, care has to be taken to check that the models of AVR's and PSS's are right for the equipment at the location were damping is to be added. Doing measurements on the equipment to check that it applies to the model would also strengthen the results. PSS tuning on the other hand has to be done off line to get sufficient results. For each location, the PSS has to be tuned according to the characteristics of the power plant.

Before commissioning, the results of implementing the strategy have to be verified by applying nonlinear simulations in a power system simulator with a detailed model of the system. This has to be done with various scenarios in order to fully verify that the strategy works. Finally the re tuned PSS can be installed according to IEEE Standard 421.5-1992 [7].

In the system there are two power plants where generators share a common pen stock, the generators therefore all have the same output which can cause problems with control. It has been shown that by placing a PSS at generators which are all equally loaded there is a possibility that in order to stabilize an inter area mode, intra plant mode damping can be decreased at the same plant [17]. This is not always the case and this was not experienced in the tuning of the PSS's in this thesis. On the other hand it is good to bear in mind when implementing the damping strategy in the real system. It has been proved that the intra plant mode is non observable if the input to a PSS is the sum of rotor speeds [18]. Therefore if problems arose of this kind this fact could be used.

Chapter 11

Conclusions

In this thesis the topic of damping in the Icelandic power system has been the focus. To be more precise it has been about the damping of oscillations in the system by using a so called PSS. The structure of the Icelandic power system has been described as well as the fundamental aspects of power system oscillations and stabilizers. The process of modeling the system is described and the methods used for analysis. Finally a strategy to damp oscillations is put forward and implemented. The last part describes the results of implementing the new strategy.

The first goal of this thesis was to do a full modal analysis of the system after increase in its capacity. This analysis is described in chapter 6, and was applied to three various test cases. The results of the analysis were that a few oscillation modes of the system were in need of increased damping. Some of these modes were even unstable under some circumstances.

The second goal of this thesis was to design a damping strategy for the modified system. The decision was taken to design a damping strategy for the system based on one type of PSS and to tune the PSS's based on modal analysis of the system without the existing PSS's. The damping strategy is based on placing a PSS at five strategic locations. Tuning of these PSS's was done and results were checked. Damping of all modes in the system was increased above 6% in all cases. Finally time simulations were done on the system with the new damping strategy implemented. The results showed that in two cases the damping was improved. In one case, synchronism was lost in the system so results could not be compared.

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Appendix A

Phase fitting in Matlab

The matlab code used for phase fitting:

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% A function to calculate the parameters of two lead-lag filters
% for compensating the phase of a transfer function.
%
% Output: sys_ll, a transfer function of two lead-lag filters
%
% Input: sys_org, the transfer function to match phase for
%        init, a vector of initial values for parameters
%        limmin and limmax, vectors of limits for parameters
%        fmin and fmax, frequency range to match for
%        phi, how many degrees to undercompensate for
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function sys_ll = mylsq(sys_org,init,limmin,limmax,fmin,fmax,phi)

% Calculating the phase to be matched
[mag_org,phase_org,w] = bode(sys_org,{fmin*2*pi,fmax*2*pi});

% Matching the phase
[theta,wval,resnom] =
        lsqcurvefit(@pss,init,w,phase_org(1,:)+phi,limmin,limmax);

% Print out the parameters
theta

% Forming the mathced transfer function
num = conv([theta(1) 1],[theta(3) 1]);
den = conv([theta(2) 1],[theta(4) 1]);
sys_ll = tf(num,den);
```

```
% The function to match phase, passed to lsqcurvefit
function phase = pss(theta,w)
sys_ll1 = tf([theta(1) 1],[theta(2) 1]);
sys_ll2 = tf([theta(3) 1],[theta(4) 1]);
sys_ll = sys_ll1*sys_ll2;
[mag_ll phase_ll] = bode(sys_ll,w);
phase = phase_ll(1,:);
```