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Electric-Hydraulic Interaction

Impact of Hydraulic Properties on Stability in
Isolated Operation

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Problem Description

Traditional tools for Power System Analysis use simplified mathematical models for the water conduit and turbine of a hydro power plant. These models neglect hydraulic phenomena such as water hammer effect and conduit elasticity, and may therefore be inaccurate and insufficient when studying a possible interaction between hydraulic system and power system. This work will consist of computer modeling and analysis of a hydro power plant supplying an island grid. A real power plant will also be modeled, and the simulations results will be compared to physical measurements from the real plant.

Abstract

The models for hydraulic systems found in standard Power System Analysis tools are often based on simplified mathematical models. These simplifications may lead to inaccurate representations of the dynamic behaviour of hydro power plants.

The objective of this Master's thesis was to study hydraulic effects and their impact on the performance of a hydro power plant from an electrical engineering point of view. A model of Riksheim power plant in Sykkylven, Møre og Romsdal has been in implemented in the hydraulic simulation tool LVTrans, in order to ensure that all hydraulic effects are included. The dynamic performance of the power plant in isolated operation was tested and compared to measurements from the real power plant.

It was discovered that the hydraulic properties of Riksheim makes it almost impossible to maintain stability in all operating conditions and at the same time satisfy all specifications made by the Transmission System Operator. It is especially the effect of water hammer that has a negative impact on dynamic performance. It was also discovered that careless selection of governor settings may cause resonance between control system and the travelling waves.

Sammendrag

Modellene for det hydrauliske system som finnes i vanlige verktøy for kraftsystemanalyse er ofte basert på svært forenklede matematiske modeller. Disse forenklingene kan føre til at viktige effekter blir utelatt og at simuleringer av dynamisk ytelse for vannkraftverk blir unøyaktige.

Målet med denne masteroppgaven har vært å studere hydrauliske effekter og deres påvirkning på ytelsen til et vannkraftverk i isolert drift. En modell av Riksheim kraftverk i Sykkylven, Møre og Romsdal har blitt laget i simuleringsverktøyet LVTrans. Deretter har isolertnettytelsen til kraftverket blitt testet og sammenlignet med måleresultater fra det virkelige kraftverket.

Resultatene viste at det er nærmest umulig å oppnå stabilitet i alle driftssituasjoner samtidig som kravene til transient respons satt av Statnett blir oppfylt. Dette på grunn av den hydrauliske utformingen av Riksheim, samt trykkstøt i rørgata. Disse effektene har en negativ innvirkning på stabiliteten. Det ble også oppdaget at uforsiktig valg av regulatorparametere kan føre til resonans mellom rørgata og kontrollsystemet.

Preface

This is my Masters thesis in TET4900 - *Energy and Environmental Engineering*, carried out at the Department of Electric Power Engineering of the Norwegian University of Science and Technology in the spring 2016

I would like to thank Trond Toftevaag, who has been my supervisor, as well as Dr Bjørnar Svingen, for contributing with his expert knowledge on the simulation software and governor tuning. I would also like to thank Sykkylven Energi for allowing me to work with, and publish information regarding their power plant, Riksheim kraftverk.

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Chapter 1

Introduction

1.1 Background

Traditional tools for Power System Analysis use simplified mathematical models for the hydraulic parts of a hydro power plant. These models assume an ideal, lossless turbine and neglect phenomena such as water hammer effect and conduit elasticity. They may therefore be inaccurate and insufficient when studying a possible interaction between hydraulic system and power system.

In relation to some previous work carried out at *SINTEF*, measurements from Riksheim power plant in Sykkylven, Møre og Romsdal were received. They showed severe oscillations in pressure and frequency that was unexpected for a power plant of this type. One of the measurements is given in figure 1.1 and shows oscillations following a small disturbance forcing the power plant into an emergency stop. It was clear that some hydraulic effect or governor issue were causing these oscillations, but not exactly what.

1.2 Objective

The objective of this thesis has been to study the hydraulic properties that affect the dynamic performance of a hydro power plant from an electrical engineering point of view. Especially in relation to the stability calculations in *Riksheim kraftverk - drift på eget nett*[1] and the measurements in *Rapport - prøving av øydrift*[2].

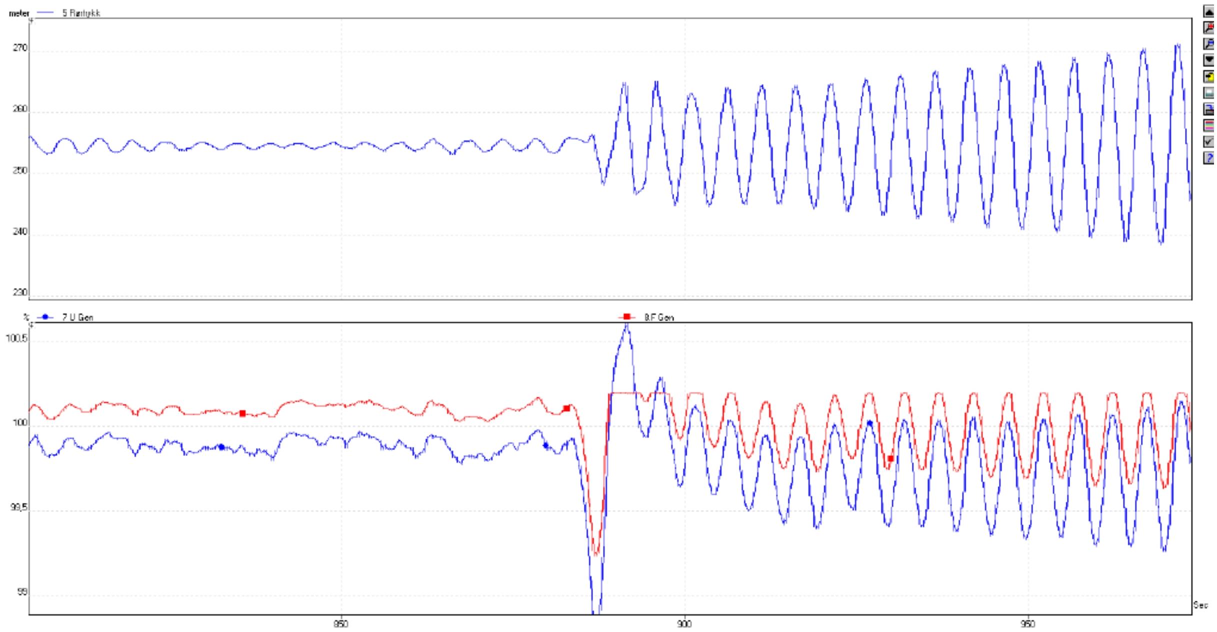

Figure 1.1: Pressure oscillations forcing Riksheim power plant into an emergency stop

1.3 Scope of Work

Implement a model of Riksheim power plant in the simulation tool LVTrans in order to compare simulation results with measurements from the real plant and analyse the dynamic performance. Investigate the validity of the stability calculations in *Riksheim kraftverk - drift på eget nett*[1].

1.4 Outline of Thesis

Chapter 2 provides the theoretical background for the topics discussed in this thesis. This includes deduction of the equations and time constants used, as well as explanations regarding important features and components of a hydro power plant.
Chapter 3 is a description of simulation software, and Chapter 4 contains descriptions of the simulation model along with physical parameters from Riksheim that was used in the simulation.
Chapter 5 presents all the simulations and results, while Chapter 6 contains discussions regarding the simulation results and theoretical stability criteria.
Finally, Chapter 7 presents the conclusions of this work.

Chapter 2

Theory

This chapter gives an introduction to the different components of a hydro power plant, and proceeds to develop the fundamental relationships and time constants used in computer simulations. This includes hydraulic phenomena that are normally neglected in power system models, such as water inertia and the water hammer effect.

2.1 Hydro Power Plants

The general layout of a simple hydro power plant is shown in figure 2.1. It consists of a reservoir, tunnel, surge tank, penstock, turbine and generator. In addition to the components already mentioned, a hydro power plant needs systems to control the electric output of the plant. The two main systems responsible for this task are the turbine governor, which controls the electric frequency by adjusting the turbine gate opening, and a voltage regulator that controls the generated voltage by means of adjusting the magnetization current.

The relationship between the different dynamics of a hydro power plant is shown in figure 2.2. The *Turbine Control Unit* will be referred to as the governor or PID controller in this text. As shown in the figure, the turbine is influenced by both speed, pressure and gate opening. The turbine output, mechanical torque, in turn affects the rotor and generator assembly and may cause speed deviations. The effect of water inertia causes turbine flow to lag behind changes in turbine gate opening[4]. This introduces phase lag to the speed governing loop, making it harder to control. The effect of water hammer is caused by travelling waves of pressure and flow in the pipe. If the penstock is long, resonance between penstock and control system may cause the water hammer to reach

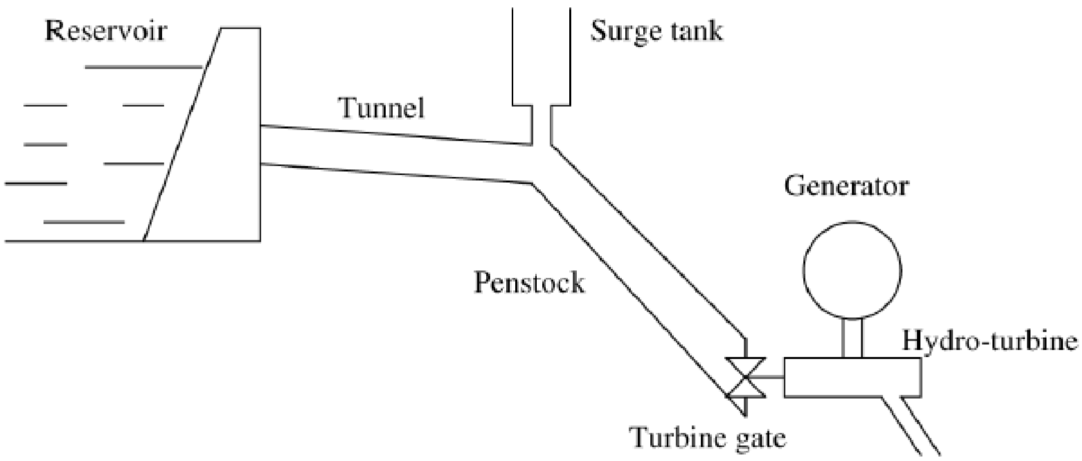

Figure 2.1: General layout of a hydro power plant[3]

destructive levels[5]. The turbine and conduit dynamics will be covered in the following sections.

2.2 Turbines

A turbine is a hydraulic device that converts the potential energy of water into rotational kinetic energy. As figure 2.2 shows, the turbine dynamics are characterised by the variation in flow and output torque as a function of speed, gate opening and pressure head. As this relationship is quite complex, the characteristics of hydraulic turbines are often depicted in diagrams called *Hill Charts*. These diagrams can be obtained by testing the turbine at various operating points and show the relationship between efficiency, speed and flow. The two basic types of turbines are: impulse turbines and reaction turbines[5].

2.2.1 The Pelton Turbine

Impulse turbines are more commonly known as Pelton wheels and are typically used for high heads. The turbine consists of stationary nozzles where the water pressure is transformed into kinetic energy. Jets of water from the nozzles then impinge on buckets mounted on the periphery of the turbine runner before discharging to the sides. Practically all of the kinetic energy is converted into torque on the runner. Important features of the impulse turbine is that there is no change in pressure across the runner, meaning that it

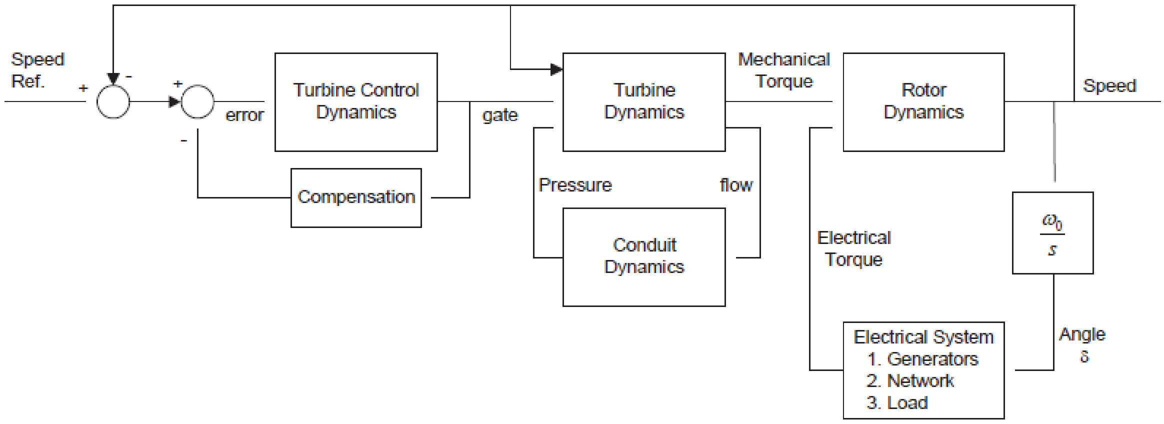

Figure 2.2: Functional Block Diagram Showing Relationship of Hydro Prime Mover System and Controls to Complete System[6]

can spin in atmospheric pressure[5]. Additionally, the open flow on the downstream side of the turbine means that pressure transients can only be induced on the upstream side. Impulse turbines are usually equipped with deflectors in front of the nozzles, in order to provide a reduction of power quicker than the water flow can be changed.

2.2.2 Nonlinear turbine model

The output mechanical power from an ideal turbine is the product of volumetric flow, q, and the available pressure, p [3]. Additionally, an efficiency factor, η, is included in order to account for power losses:

$$P_m = \eta q \rho g_a h \tag{2.1}$$

Another way to account for the turbine efficiency is to subtract the no-load flow, q_{nl}, from the net flow, thus producing an effective flow. When the turbine is operating off nominal speed, a damping effect will be present. The damping is a function of gate opening, G, speed deviation, $\Delta\omega$, and is related to the output power by means of a damping factor, K_D. The per unit turbine power can the be expressed as [5]:

$$P_m = A_t h(q - q_{nl}) - K_D G \Delta\omega \tag{2.2}$$

where the turbine gain, A_t, is a constant proportionality factor relating turbine power to generator power and can be calculated using:

$$A_t = \frac{1}{G_{fl} - G_{nl}} \times \frac{Turbine MW rating}{Generator MW rating} \tag{2.3}$$

where G_{fl} is the gate position at full load. The per unit flow rate through the turbine can be related to gate opening and head by assuming the turbine can be represented by the valve characteristic:

$$q = G\sqrt{h} \tag{2.4}$$

2.3 Water Conduit

Hydraulic transients in a closed conduit consist of pressure fluctuations and in hydro power plants these transients occur when the flow through the turbine is changed, following an adjustment from the governor. As can be seen in figure 2.2, the conduit dynamics will greatly influence the effective head, which in turn has a large impact on the turbine. In fact, the behaviour of the water in the conduit, and the layout of the conduit may cause instability to the entire system and is a common governing problem[5]. This is especially true for many Norwegian plants where long and complex tunnel systems are common.

2.3.1 Inelastic water column

In this first section, a simple penstock without surge tank is examined. In any rigid conduit, head loss will occur as a consequence of friction between the conduit and the water. The head loss due to friction, h_f, is proportional to the flow squared:

$$h_f = f_p q^2 \tag{2.5}$$

where f_p is the head loss coefficient. Assuming the water to be incompressible and the conduit walls to be perfectly rigid, the per unit rate of change of the water flow may be expressed as[7]:

$$\frac{dq}{dt} = \frac{1 - h - h_f}{T_w} \tag{2.6}$$

where h is the head at the turbine inlet and h_l is the head loss due to friction. The water starting time, T_w, is a time constant reflecting the acceleration time of water in the penstock between turbine inlet and the reservoir, and is defined as:

$$T_w = \frac{L}{A}\frac{q_{base}}{h_{base}g} \tag{2.7}$$

where L and A is the length and area of the penstock, g is the acceleration du to gravity. q_{base} is the flow at full gate opening with head equal to the total available static head, h_{base}.

2.3.2 Elastic water column

When the penstock is long, it is necessary to consider the effect of water hammer, which is a consequence of the elasticity of steel and the compressibility of water. The phenomenon is caused by a rapid acceleration or deceleration of the water flow, and consists of pressure waves which travel back and forth in the penstock. The wave travel time, T_e, is defined as the time taken for the pressure wave to travel from the turbine inlet to the nearest free surface, and is given as[5]:

$$T_e = \frac{L}{a} \tag{2.8}$$

where a is the pressure wave velocity. Typical values for this velocity are in the range of 1000-1200 m/s[7]. The differential equations of continuity and motion for a pipe section is given as[8, p. 28]:

$$\frac{\partial h}{\partial t} + \frac{a^2}{g}\frac{\partial v}{\partial x} = 0 \tag{2.9}$$

$$g\frac{\partial h}{\partial x} + \frac{\partial v}{\partial t} + \frac{f}{2D}V|V| = 0 \tag{2.10}$$

where x denotes the distance from the left end of the pipe, D is the diameter and v is velocity.

2.4 Turbine Governor

The purpose of the turbine governor is to control speed and load by adjusting the needle openings of the Pelton turbine. This is a crucial task during islanding conditions, since the turbine speed is directly correlated to the electric frequency of the power system. Speed control involves feeding back the speed error through a droop characteristics as the basis for the needle opening control. The permanent droop R_P determines the speed regulation under steady state conditions and is defined as the required speed deviation necessary to cause a 100 % change in gate position[7, p. 172]. Regulation during transients is performed by the three-term PID-controller, as shown in figure 2.3.

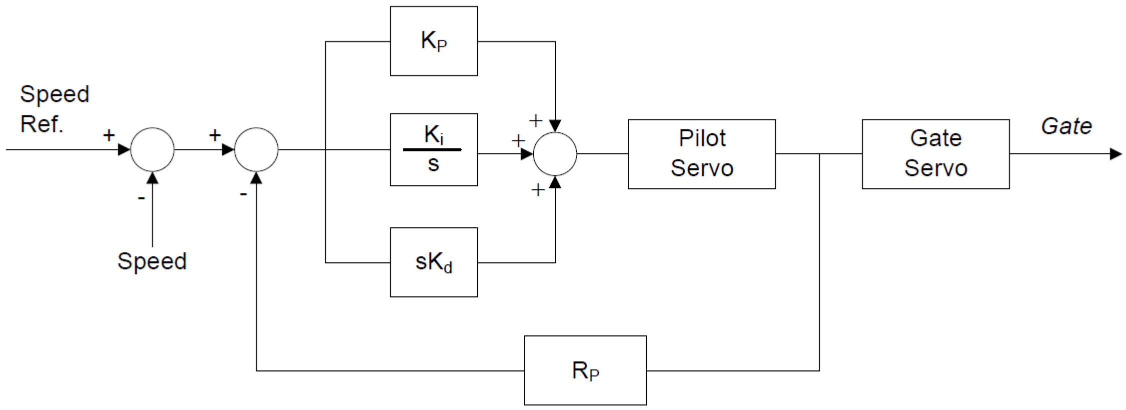

Figure 2.3: Block diagram of speed governor for hydraulic turbines. From [4, p.404]

The proportional gain produces a immediate controlling action proportional to the the magnitude of the error between reference speed and actual speed. This means that a pure proportional controller will never be able to reach the reference speed on its own as the controller output will approach zero when the error approaches zero, resulting in a steady-state error. The integral term produces a controlling action that is proportional to the time integral of the error, meaning that a error sustained over some time will result in a stronger output from the controller in order to eliminate any steady-state error. The derivative term will not be considered in this thesis.

2.5 Stability based on Frequency Response

One way of evaluating the stability of a system is to study the frequency response to a system disturbance. This frequency response may be presented in a Bode-plot showing gain and phase angle as a function of frequency, as shown in figure 2.4. From this plot two important measures of stability can be extracted: Gain and Phase margin. Crossover frequency is the point where the gain crosses the 0 dB-line. Phase margin in the Bode-plot is the difference between the phase and -180 degrees at the crossover frequency, and thus denotes the amount of negative phase shift that can be tolerated before system becomes unstable. The Gain margin is the distance between the 0 dB-line and the gain at the point where the phase crosses -180 degrees. This is a measure of the gain increase that can be tolerated before the system becomes unstable.

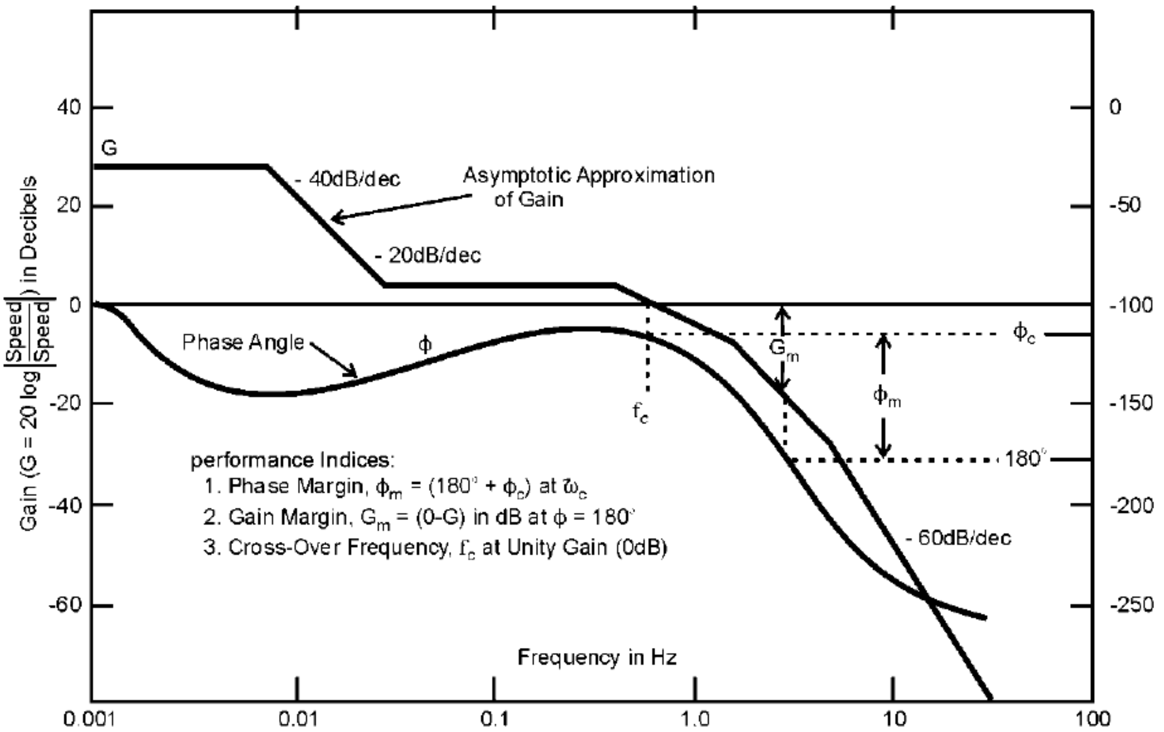

Figure 2.4: Bode-plot of frequency response. From [9, p. 104]

Chapter 3

Simulation Software

LVTrans is a dynamic simulation tool for systems of liquid-filled pipes and open channels. The program is general of nature, but it is specialised towards dynamic simulations of hydro power plants. LVTrans is object oriented and built on the graphical interface of LabVIEW, allowing the user to drag and drop elements from a toolbox and build them into a system. All elements needed to build a hydro power plant is included in the toolbox, and can be used without any knowledge of the source code. More information regarding the functionality of the various elements as well as a method for tuning PID-governors can be found in the *LVTrans manual*[10].

LVTrans relies on the *Method of Characteristics* to solve the partial differential equations of the elastic water column[11, p. 101]. This allows for fast solving in the time domain, without any loss of accuracy. Turbines in LVTrans are calculated using dynamic equations developed by Professor Torbjørn Nielsen, rather than through static *Hill Charts*. This ensures a correct representation of the physics during transients[10, p. 23].

Chapter 4

Simulation Model

This chapter contains descriptions of the model implemented in LVTrans as well as the physical data from Riksheim power plant that was used in the computer simulations.

4.1 Model Description

A model of Riksheim power plant was implemented in LVTrans based on the descriptions from the two reports [1] and [2]. The layout of the plant is very simple, comprising only a small reservoir, a penstock and a Pelton turbine connected to a synchronous generator, as well as the necessary gates and valves. This simplicity is reflected in the LVTrans block diagram, shown in figure 4.1. The outlet pipe and outlet reservoir to the right are not mentioned in the physical description of Riksheim, but are included in order to get a complete model. Because of the hydraulic separation between inlet and outlet of a Pelton turbine, these components will not affect the simulation results in any way.

The reservoirs to the left and right are implemented as constant pressure sources. The pipes are general liquid filled conduits for dynamic calculations including elastic effects. The Pelton turbine is fully dynamic and includes pole oscillations. The PID element is an implementation of a standard three-term PID controller with opening related droop. Not much is known regarding the specifics of the generator implementation in LVTrans, except that it is "simple". The grid is implemented as constant voltage, purely resistive. But as the specifications regarding stability set forth by the Transmission System Operator requires testing and tuning to be performed as if the power plant was supplying an isolated, purely resistive grid[12, p. 95], this leaves the generator model as the only uncertainty in terms of the precision of the system. The results of the simulations performed in this

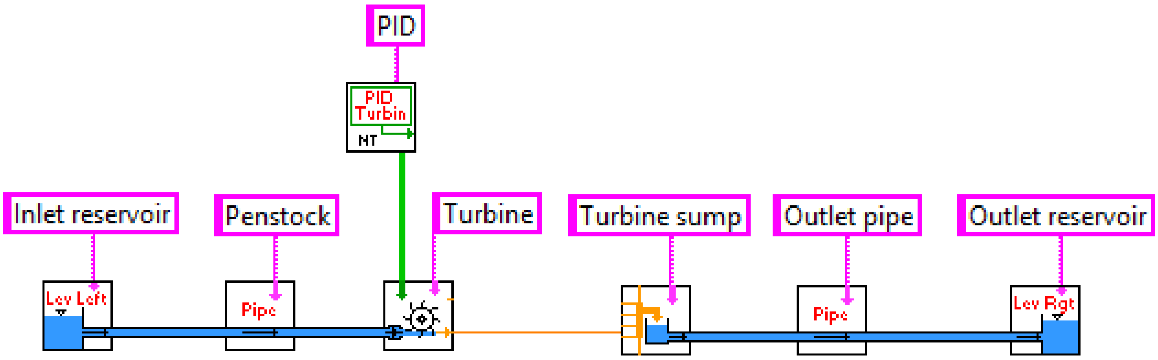

Figure 4.1: Block diagram of the LVTrans implementation of Riksheim powerplant.

thesis should be valid and within specifications nevertheless.

4.2 System Parameters

The parameters used for the hydraulic models are given in table 4.1. The element names in the table correspond to the pink boxes in figure 4.1. Most of the data in this section was extracted from the documents [1] and [2]. In cases where necessary information was not given in the two documents, standard values from LVTrans or relevant literature was used. Parameters for the turbine sump, outlet pipe and outlet reservoir are not included as they do not affect the simulation. Some parameters for the PID element are missing from table 4.1 and will be covered later, as they are related to the tuning of the PID element rather than being physical parameters.

Table 4.1: Parameters for LVTrans model

Inlet reservoir		Value
H_0	Pressure head from datum	317 m
Penstock		Value
L	Length of pipe	1150 m
D	Diameter	1.2 m
F	Friction constant	0.01
Z_0	Height from datum, left end	317 m
Z_1	Height from datum, right end	57 m
Q_0	Initial volumetric flow	2.31 m^3/s
H_0	Initial pressure head, HGL	317 m
Turbine		Value
Q_r	Rated volumetric flow	2.31 m^3/s
H_r	Rated head	260 m
N_r	Rated angular velocity	600 rpm
T_r	Rated torque	Nm
T_a	Time constant, rotational inertia	2.7 s
$Poler$	Number of poles in the generator	10
$n\_needles$	Number of needles	6
PID		Value
P_r	Rated power	5.37 MW
N_r	Rated angular velocity	600 rpm
SP_0	Initial power set point	5.37 MW

Chapter 5

Governor Tuning and Performance Analysis

This chapter is dedicated to the tuning of the PID element parameters. The stability of the power plant is then evaluated based on control engineering principles and the stability requirements made by the Transmission System Operator. The specifications from the TSO are given in the document *Funksjonskrav i Kraftsystemet*[12] and will be referred to as FIKS.

5.1 Governor Tuning

The turbine governing system used is a standard implementation of a three-term electro-hydraulic governor. A block diagram as well as explanations of the various parameters is given in section 2.4.

The first step in the governor tuning process is to determine the regulator closing time. That is, the time spent changing the nozzle opening from fully open to fully closed. The closing time has to be set sufficiently high so as to avoid excessive pressure in the penstock. The maximum pressure rise for Riksheim is set to 15 %. Then the closing time can be determined by simulating a full stop from various loads and increasing the closing time until the following criterion is met:

$$H_2 \leq 260m + 15\% = 299m \tag{5.1}$$

where H_2 is absolute pressure measured at the lower end of the penstock. A closing time of 18.0 seconds results in the pressure transient shown in figure 5.1 for a full stop from 20% load. As the figure shows, the pressure never exceeds $299m$ and it is concluded that a closing time of 18.0 seconds is sufficient to ensure the maximum allowed pressure rise is never exceeded.

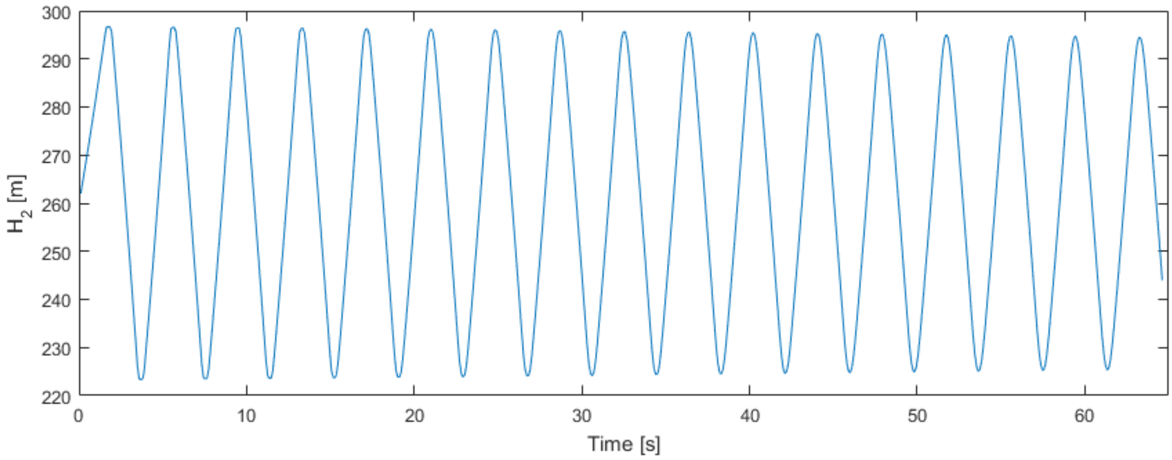

Figure 5.1: Testing of regulator closing time. Absolute pressure in lower penstock

The PID-parameters are tuned according to the method described on page 33 of the LVTrans manual[10]. This method involves changing the speed setpoint back and forth while adjusting the PID-parameters to get the desired response. The final parameters are given in table 5.1. As the governor tuning has to be performed[10, p. 33], and most of the simulations are performed in isolated operation, the permanent droop is set to 0. This would not be the case in regular interconnected operation, where the value for permanent droop usually would be set in the range 1% - 12% according to the relative size of the power plant in the grid it is operating in[12, p. 34].

Table 5.1: Governor Settings

Parameter		**Setting**
K_P	Proportional gain	1.2
T_i	Integral time constant	2.1 s
T_d	Derivative time constant	0.0 s
T_{close}	Regulator closing time	18.0 s
R_P	Permanent droop	0

5.2 Stability Analysis

LVTrans has a built in tool for stability analysis. It is based on frequency-response analysis of time-series using the Fast Fourier Transform. The output from this tool is a Bode-plot of the system as well as the three main variables used to evaluate stability: *Phase margin,* Ψ, *Gain margin,* ΔK, and *Deviation ratio, N.* These variables were further explained in section 2.5.

5.2.1 Stability Criteria

The general stability of a feedback control system may be characterised by it's gain and phase margin or by its deviation ratio. These are readily available in the LVTrans stability analysis tool, and are also used in literature and grid codes to specify satisfactory stability. Some suggested limits from various literature are shown in table 5.2. It is worth noting that FIKS specifies both an upper and lower limit. In addition to the limits in table 5.2, the LVTrans manual and *Reguleringsteknikk*[13] both state that stability can equivalently be specified by the deviation ratio, and suggests the following stability limit: $|N(j\omega)|\,\text{max} \leq 6$ [dB].

Table 5.2: Stability limits in various literature

Source	**Suggested limits**	
FIKS 2012[12, p. 95]	$25 \leq \Psi \leq 35$ [deg]	$3 \leq \Delta K \leq 5$ [dB]
Brekke[11, p. 71]	$\Psi \geq 30$ [deg]	$\Delta K \geq 3$ [dB]
IEEE-standard [9, p. 108]	$\Psi \geq 40$ [deg]	$\Delta K \geq 3$ [dB]

5.2.2 Stability at Tuning Conditions

The results of the stability analysis for Riksheim at tuning conditions is shown in the Bode plot in figure 5.2. From the Bode plot the variables chosen to evaluate stability can be extracted. These are given in table 5.3 and show that the power plant is well within the minimum limits given in the previous section. However, the phase and gain margins are also above the maximum limits given in FIKS. This is an indication that the turbine is very stable, but might be too slow to satisfy the requirements for transient response.

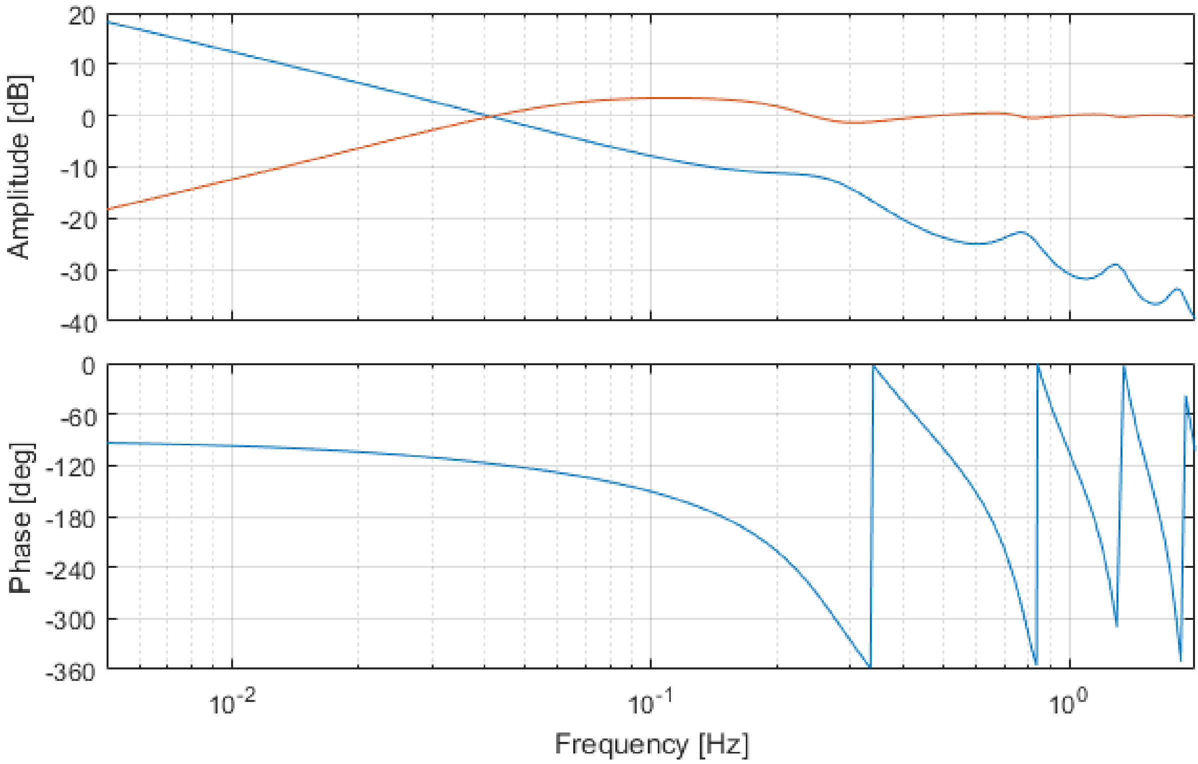

Figure 5.2: Bode-plot showing stability at tuning conditions

Table 5.3: Stability at tuning conditions

Parameter		**Value**
Ψ	Phase margin	62.5 [deg]
ΔK	Gain margin	10.27 [dB]
$\lvert N \rvert$ max	Deviation ratio	3.44 [dB]

5.2.3 Stability in Various Operating Conditions

The stability was also tested at various other operating points, with different numbers of nozzles in operation. The results from these tests are shown in figure 5.3 for operation with 2, 4 and 6 nozzles active in different load conditions. By comparing the figure with the stability limits in table 5.2 it can be seen that needle sequencing is necessary in order to achieve stable operation throughout the entire loading range. 4 needles seems to give the best results for isolated operation at low loads.

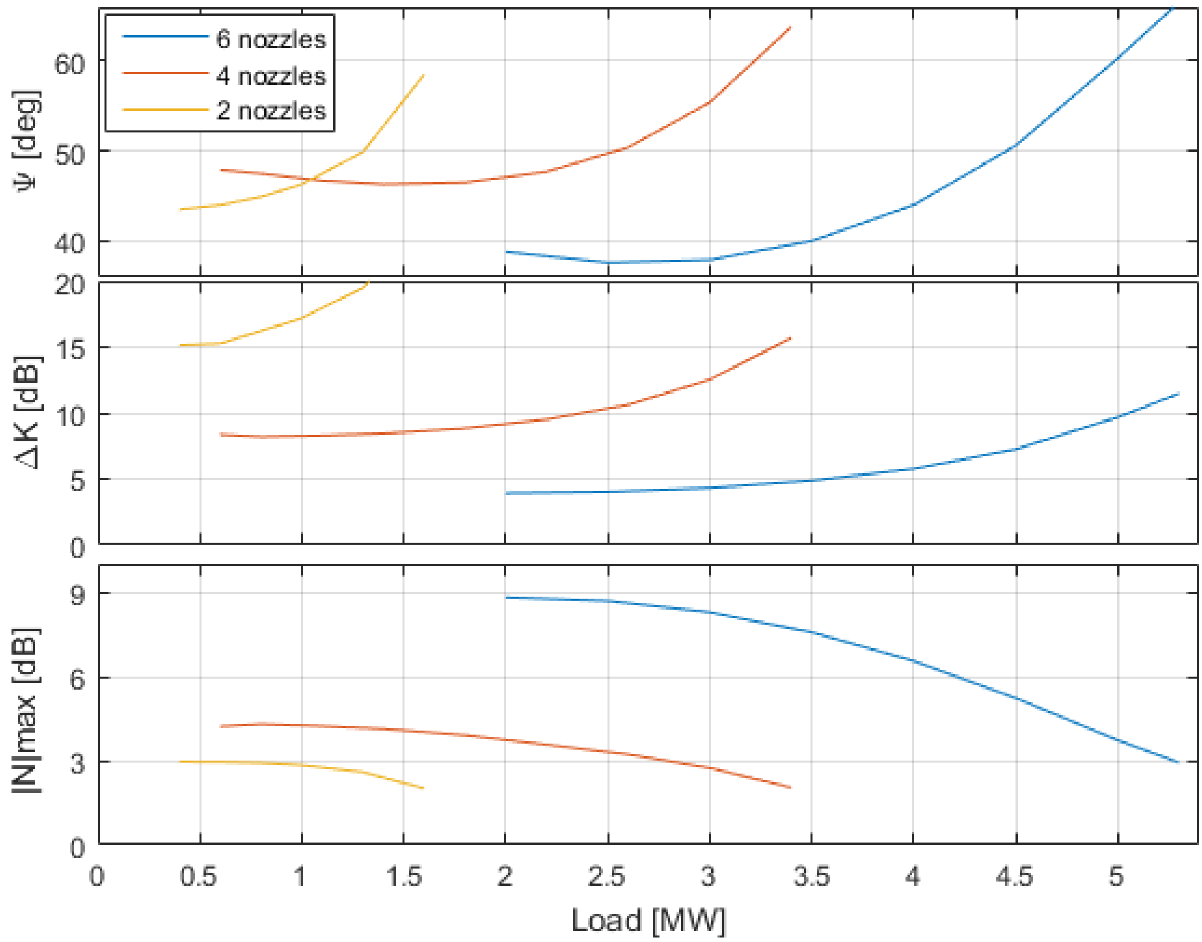

Figure 5.3: Stability in various operating conditions

5.3 Transient Response

The next step in evaluating the dynamic performance of a hydro power plant is to look at the transient response. Particularly, it is necessary to look at the power plants ability to maintain frequency within acceptable limits following a change in the operating conditions.

5.3.1 Reconstruction of Measurements from Riksheim

In order to evaluate the dynamic performance of the LVTrans model an compare it to the real power plant, the tests that were carried out on Riksheim and reported in [2] was reproduced in LVTrans. All the tests are transitions from interconnected operation to isolated operation, where the difference in generated power before disconnecting and the island load after disconnecting constitutes a step change in load. Because the governor settings were changed during testing, only the tests done after the change has been reproduced. All tests were reproduced both with 2, 4 and 6 needles operating. Needle sequencing mid-test has not been simulated. In the following, the given test numbers refers to the section numbering in the report on island operation[2].

Test 7.2

The first simulated test is a transition from interconnected operation where the power plant is providing 0.54 MW over to an island with a load of 0.65 MW. Thus the power plant will experience a 0.11 MW step change in load. The measurements from Riksheim are given in figure 5.4 where the transition happens after approximately 760 s. Figure 5.5 shows the simulation results for the same test, where the transition happens at t=10 seconds.

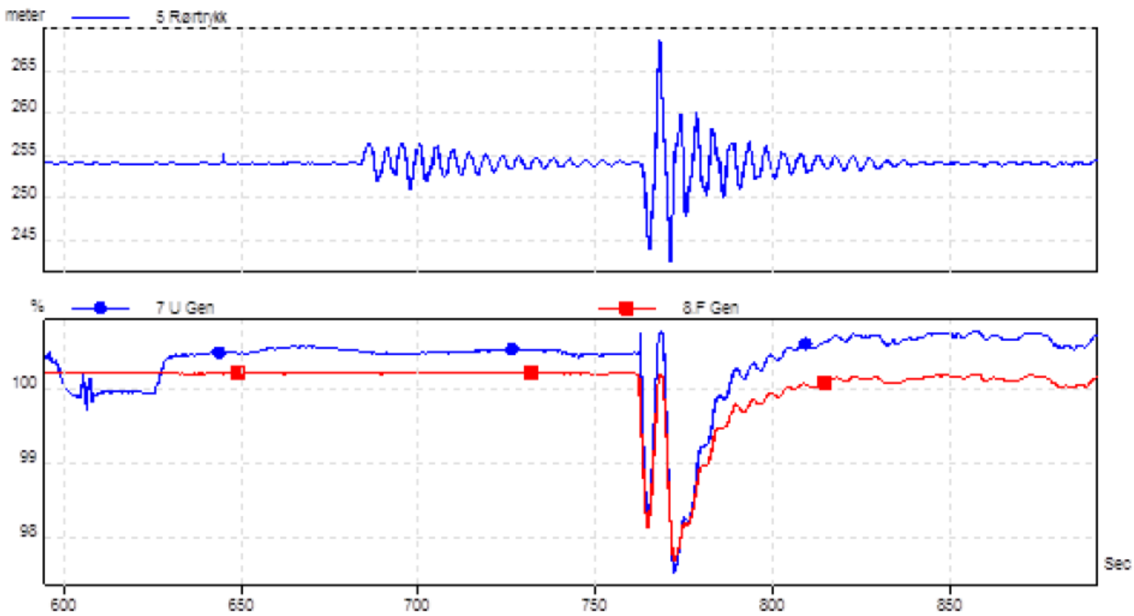

Figure 5.4: Test 7.2 - measurements

In the measurements, two distinct dips can be seen in the frequency plot. The first is obviously the point at which the main grid is disconnected. The second is probably a needle sequencing, where the governor opens up all needles to get a faster response. Because of this, the most accurate way to compare the measurements with the simulation results would be to measure the frequency deviation of the first dip against the simulation results with 2 nozzles open, and compare the time taken to stabilise the frequency against the simulation results with 6 nozzles open. In doing so, it can be observed that the frequency deviation is approximately equal, while the simulation is much quicker to reach nominal frequency. Another detail worth noticing is that the pressure fluctuations is much smaller in the simulations than in the measurements, indicating that the governor settings might be a bit more conservative than in reality.

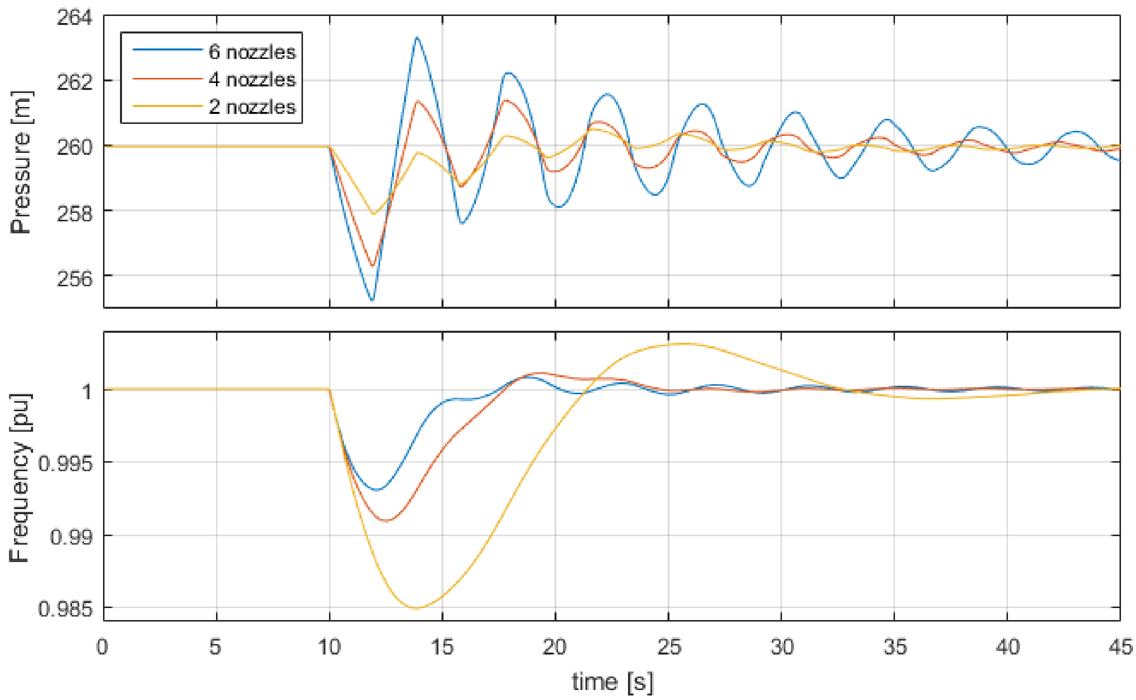

Figure 5.5: Test 7.2 - simulation results

Test 7.4

The second test is a transition from 1.25 MW interconnected power to 1.1 MW in isolated operation, resulting in a -0.15 MW step change in load. In this test, only the frequency measurement from Riksheim was given, and is shown in figure 5.6. There is no distinct evidence of any needle sequencing in this frequency plot. The simulation results include both frequency and pressure in the penstock. This is shown in figure 5.7. The measured frequency deviation is approximately 0.9 Hz, or 0.018 pu. In the simulations, the frequency deviation was 0.023 pu for operation with 2 open nozzles and 0.013 pu with 4 open nozzles. Operation with 2 active nozzles would be the most probable operating condition in this case, and without needle sequencing the graph for 2 open nozzles should be a fairly accurate representation of reality.

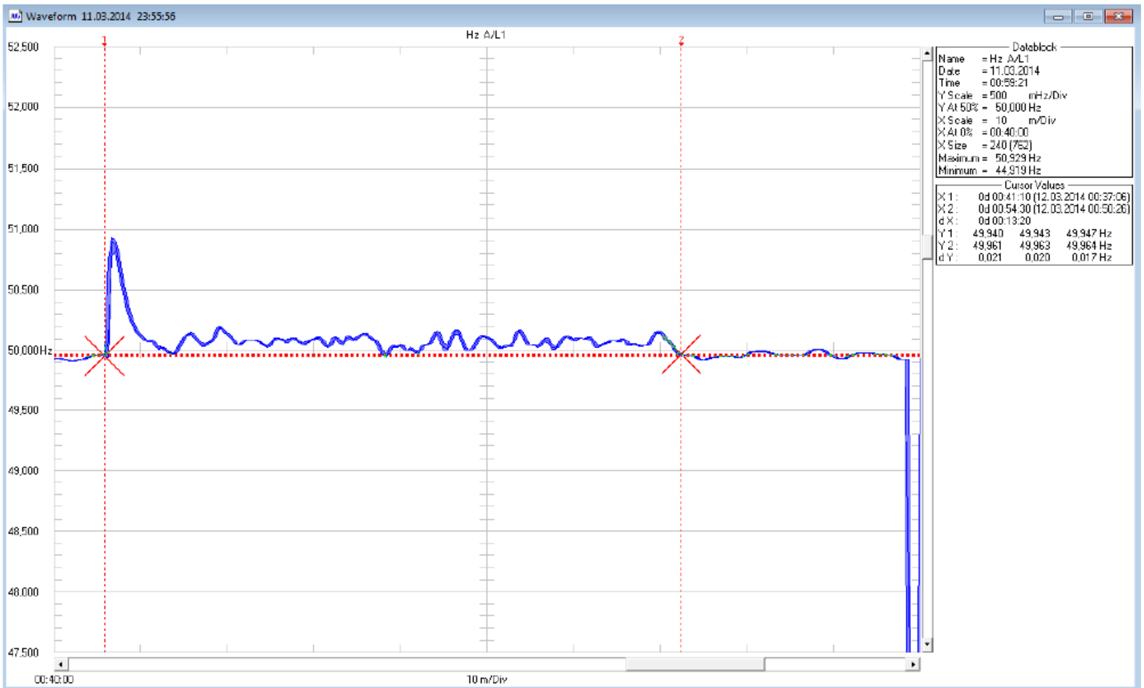

Figure 5.6: Test 7.4 - measurements

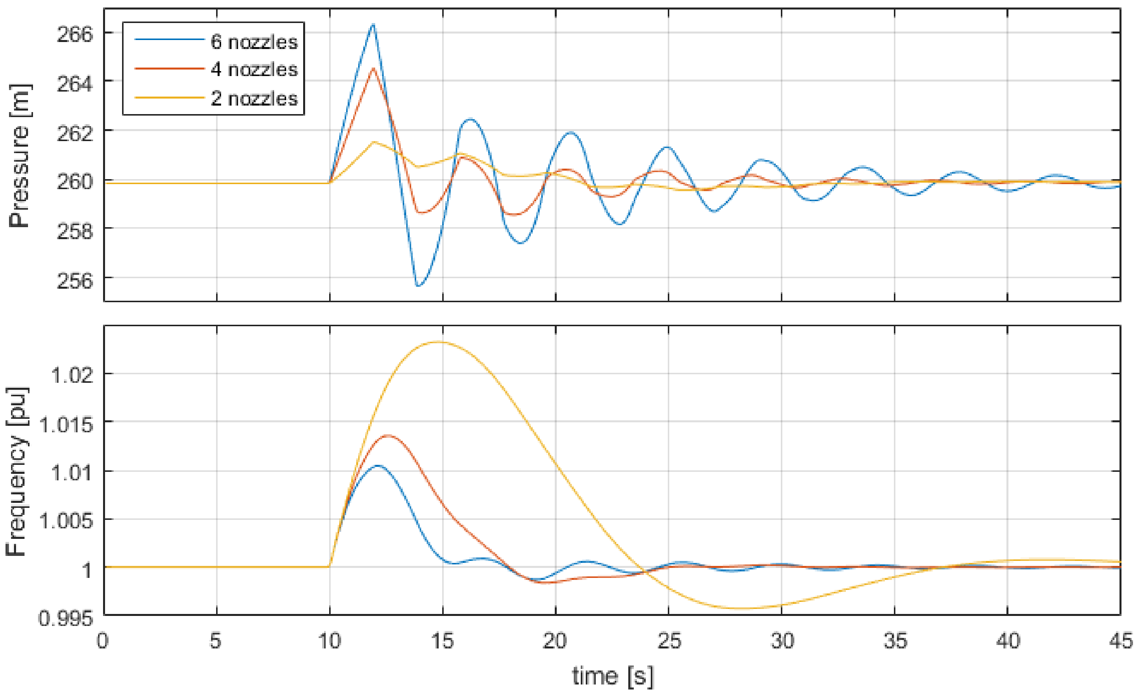

Figure 5.7: Test 7.4 - simulation results

Test 7.5

The last test that was simulated is a load change of 0.37 MW, starting with the power plant supplying 0.69 MW in interconnected and transitioning to 1.06 MW in isolated operation. The measurements from Riksheim are shown in figure 5.8, and the most important thing to notice is that the frequency slows down to under 45 Hz, causing the underfrequency protection to trip. In the simulation results, shown in figure 5.9, the generator does not slow down quite as much, and the generator would stay online for all three needle combinations. It is worth noting that this load change is significantly larger than what is calculated to be possible in [1], and on that basis it is not surprising that the power plant slowed down enough to trip the underfrequency protection.

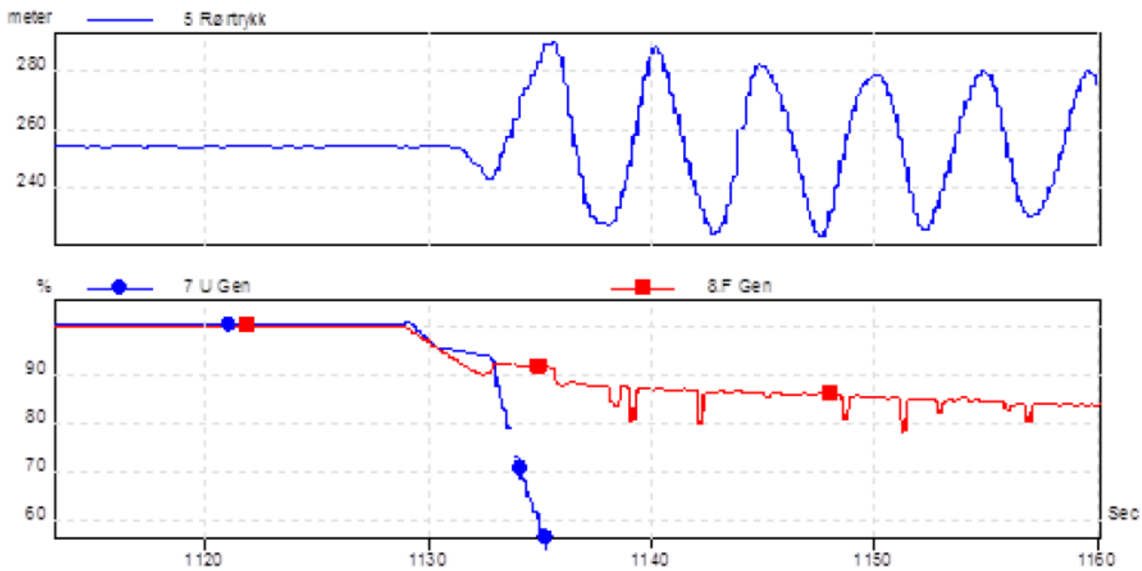

Figure 5.8: Test 7.5 - measurements

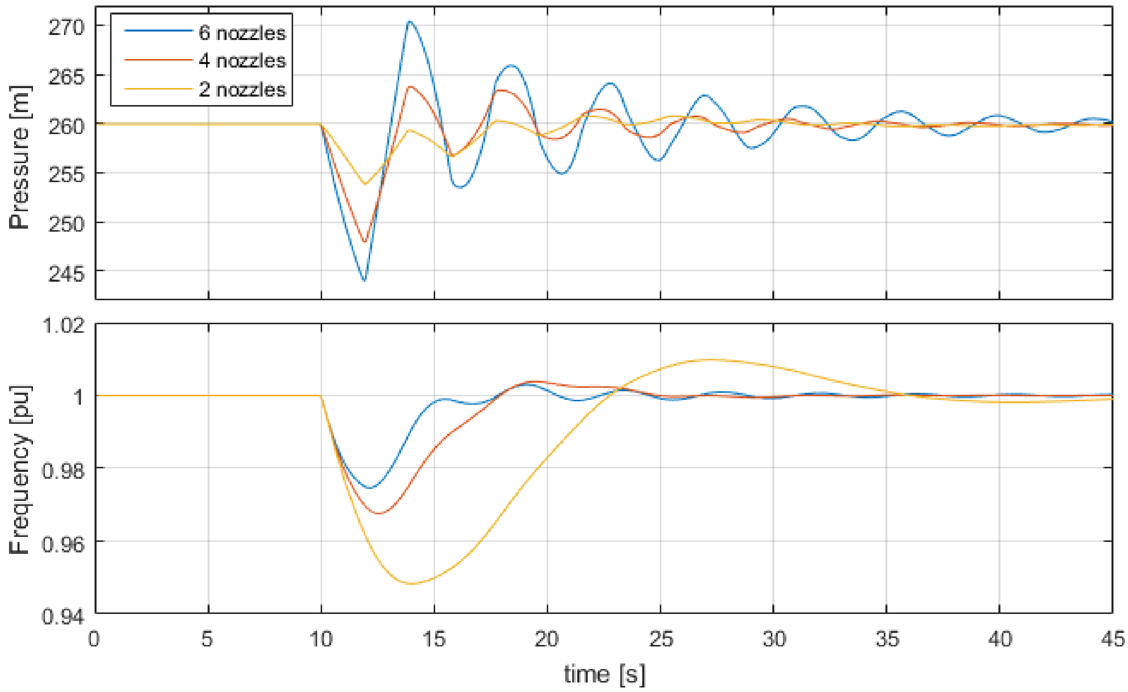

Figure 5.9: Test 7.5 - simulation results

5.3.2 Comparison With Specifications in FIKS

The guidelines given by the TSO suggests some limits for acceptable frequency deviations following a step change in load not greater than 10 % of the rated power. These specifications applies to generating units larger than 10 MVA, and to units between 1 and 10 MVA if they are equipped with proper turbine governors[12, p. 34]. The limits are shown as black lines in figure 5.10. In addition to the limits, the measured and simulated frequency deviations are shown as red and blue dots, respectively. It is clear from the figure that all of the frequency deviations are well outside the recommended limits. 2 out of 3 tests were performed at loads outside of the linear area specified by Statnett, but the results are so far outside the limits anyway, that nonlinearities should not be a decisive factor.

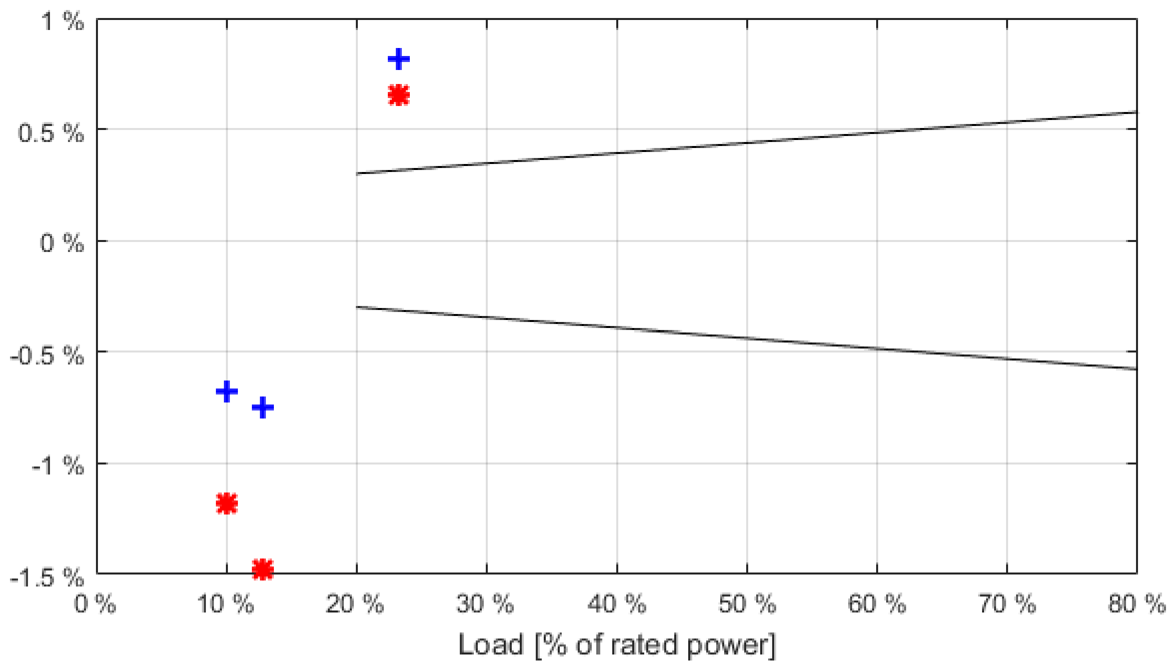

Figure 5.10: Maximum allowed frequency deviation per percent load change[12, p. 97]

Chapter 6

Discussion

6.1 General Stability Criteria

A common way of estimating a power plants ability to regulate frequency in isolated operation, is to look at the relationship Ta/Tw. That is, the rotational inertia of the generating unit versus the water starting time. It is quite intuitive that the higher the rotational inertia is compared to the inertia of the water column, the more stable the system becomes. This measure of stability is a standard rule of thumb and is commonly referenced in literature and standards. FIKS states that the relationship Ta/Tw should be higher than 4[12, p. 37]. Brekke[11, p. 130] has a table of recommended Ta/Tw ratios and Nielsen[8, p. 74] states that Tw should be smaller than 1 second in order to achieve good stability in power plants with rotational inertia in the area of 5-7 seconds. However, there are conditions to using these criteria that are not always considered. On page 22 of [9] it is said: *When the wave travel time approaches 25% of the TW, engineers should not rely on only the classic value of* T_W*, and the performance of the turbine governing system should be evaluated by considering the effects of both the water starting time and the wave travel time.* Nielsen also mentions this criteria, saying that for long penstocks the water elasticity will cause a lowering of the phase margin, and that the ratio Tw/Te has to be larger than 1 in order to effectively calculate stability on the basis of rotational inertia and water starting time.

6.2 Stability and Transient Response of Riksheim

One of the reasons for choosing Riksheim power plant as the test subject of this thesis was the powerful oscillations, shown in figure 1.1, that forced the power plant into an emergency stop. During the initial stages of implementing and testing the LVTrans model of Riksheim it was discovered that the simulation model is extremely susceptible to oscillations as well. In fact, it will start oscillating completely on its own if the PID parameters are set incorrectly, and the power plant is operated at low loads with all 6 nozzles open. An example of this is shown in figure 6.1, which is a reproduction of test 7.2, but this time with the proportional gain, $K_P = 2.0$. Seeing as Pelton turbines are considered to be stable *"no matter what values are put in"*[10, p. 38], the severe oscillations that were experienced both in measurements and simulations are a bit surprising.

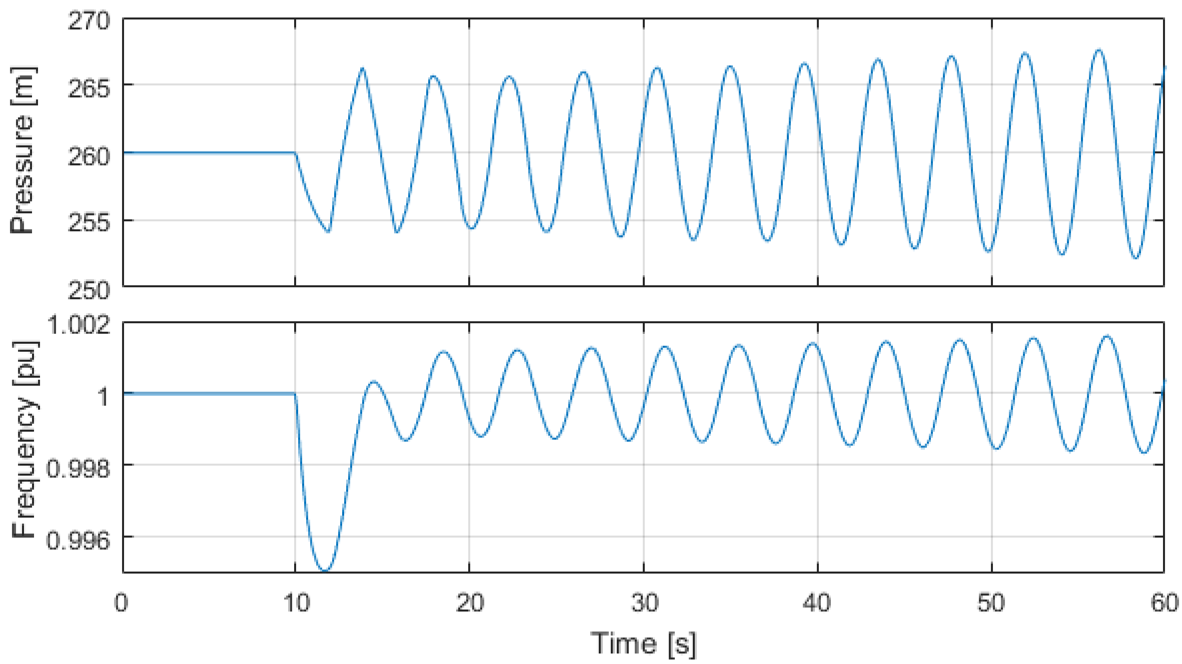

Figure 6.1: Oscillations caused by too aggressive governor settings

6.2.1 Reasons for the Poor Dynamic Performance

When studying the hydraulic layout of Riksheim as well as details about the turbine governing system, a couple of problems emerge that have a significant negative impact on the dynamic performance.

The first, and most obvious issue with the controllability of Riksheim is related to the long penstock and (relatively) low rotational inertia. As mentioned in section 6.1, the ratio of rotational inertia to water inertia is the most basic stability criteria. A plot of the ratio Ta/Tw for Riksheim is shown in figure 6.2, where the green area indicates good stability in isolated operation, the yellow indicates acceptable stability and the red poor stability. From the figure it is clear that the ratio is only within the prescribed limit at loads lower than 3.5 MW with all nozzles open.

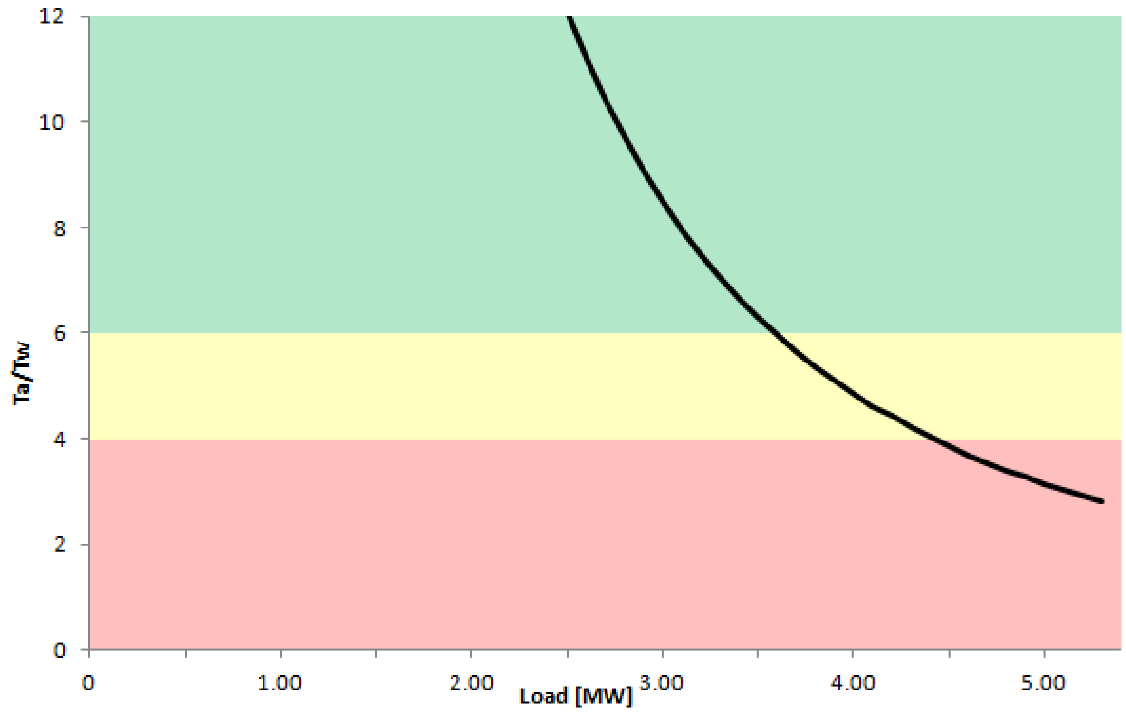

Figure 6.2: Hydraulic Stability based on Ta/Tw

The second problem is related to the effect of water elasticity. As mentioned in section 6.1, when the wave travel time approaches the same magnitude as the water starting time, the effect of water elasticity becomes significant. For Riksheim, the wave travel time is approximately 1.92 seconds, and the water starting time is 0.92 seconds at nominal power. Thus, the effect of water elasticity is actually very significant and will have a negative effect on the phase margin of the system[8, p. 74]. The crossover frequency of the system may end up in the same range as the governor is operating in, causing resonance between the travelling waves and the control system, if the governor settings are not carefully chosen. The frequency of the pressure oscillations, both measured and simulated, is approximately 0.22 Hz. By assuming the wave velocity to be 1000 m/s, the natural period for the travelling pressure waves is given by[14, p. 4]:

$$T_{th} = \frac{4 * L}{a} = \frac{4 * 1150m}{1000m/s} = 4.6s \tag{6.1}$$

This corresponds to a frequency of ≈ 0.22 Hz, proving that the oscillations is in fact caused by undamped travelling waves. This means that stability analysis on the basis of the Ta/Tw ratio is not sufficient to determine the controllability of Riksheim.

In addition to the factors already mentioned, there are two details about the governor that further inhibits the dynamic performance of the power plant. The first is related to the long closing time of the regulator. Since the closing time is so much higher than the integral time of the PID controller, the servomotor that adjust the needle position will work much slower than the signal from the PID. Thus, after a disturbance, the servomotor rate of change will enter saturation and cause the intergral term of the PID to integrate far beyond the actual error. This is known as integral windup, and causes the system to overshoot its target, causing a new disturbance.

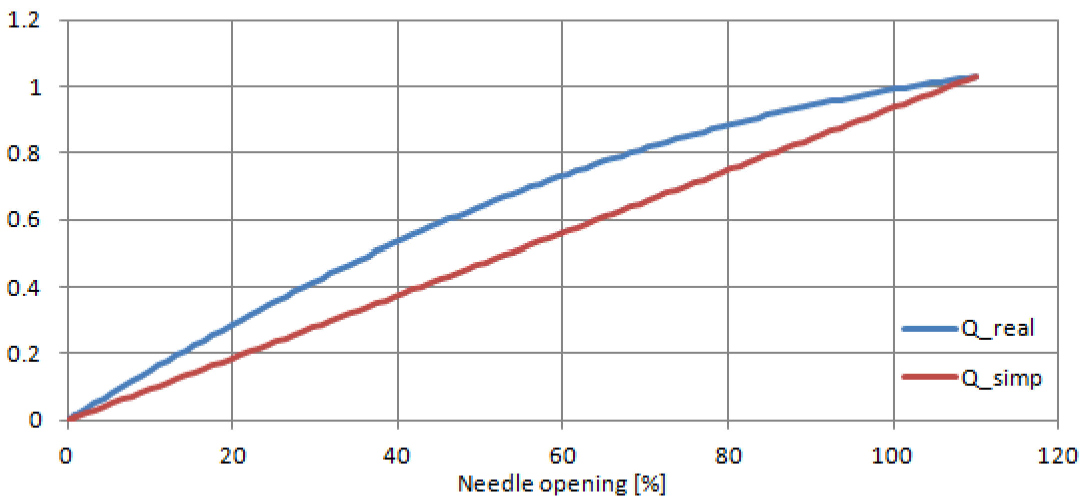

Figure 6.3: Pelton needle characteristic showing flow as function of needle opening

Additionally, a PID controller is a linear device, while the system it is controlling, the needle openings, is nonlinear. A needle characteristic from LVTrans is shown in figure 6.3, where it can be seen that the slope is much steeper in lower regions than the upper half. This means, that for a 1 percent change in output from the PID, the effective change in water flow might be much higher. This in turn means that the effective gain of the control loop is much higher at low needle openings, than it is at high needle openings. From figure 6.1 it is known that increased gain at low loads with all 6 nozzles operating is very unfortunate, as it will induce oscillations.

6.2.2 Possible Measures to Improve Dynamic Performance

It is very difficult (or expensive) to change anything about the hydraulic properties of a power plant after it is built. However, several changes can be made to the way the governor operates. First of all, as figure 5.3 shows, and as was mentioned in the previous section, it is very unfortunate to operate with all nozzles open at low loads. Thus, the governor should be prohibited from opening up all 6 nozzles at low loads, and instead run with 4, or even fewer nozzles open. This solution was also suggested by Sweco in [1, p. 6] and will result in a slower, but much more stable power plant. Sweco suggests in the same document that Riksheim power plant should be stable at loads up to 3.0 MW in isolated operation. It is important to note that this does not mean the power plant is necessarily unstable at full load, it just won't be able to deal with a disturbance within the frequency limits defined in FIKS.

Statnett requires generating units to run on the same governor settings in isolated and interconnected operation as a main rule, but also mentions that in special circumstances the governor may switch between several parameter sets to improve controllability in isolated operation at low loads[12, p. 95]. By utilising this option, it may be possible to shut down 2 nozzles, consider the plant to be a 3.0 MW, 4 nozzle generating unit, and tune the governor according to this. The problems related to elastic effects would still be there, but it might be possible to find more optimal PID parameters for this type of operation and have the governor switch automatically between parameter sets.

6.3 Limitations

The computer software used in this thesis uses fully dynamic equations and the method of characteristics to solve differential equations for the water conduit. The implemented model of Riksheim contains only to most important elements of the power plant, but the results should be sufficiently accurate for the purpose of this thesis. The implemented generator model in LVTrans is very simple, and may as such be a source of error. Additionally, the data for Riksheim power plant used in the computer simulations were extracted from written sources that is not consistent in the use of symbols and names, making it difficult to interpret some of the data. The reports that this work is based on also mentions island operation with two power plants supplying a small grid. This has not been considered in the thesis.

Chapter 7

Conclusion

This work has consisted of computer modeling and analysis of hydro power plant supplying an isolated grid as well as literature studies into the world of hydraulics. Riksheim power plant in Sykkylven, Møre og Romsdal, was chosen as the test subject because of the severe pressure oscillations and problems related to stability that were measured there. In order to ensure that all hydraulic effects are properly included, it was chosen to simulate the system in the simulation tool LVTrans.

Through various simulations it as been established that the hydraulic properties of Riksheim makes it very difficult to achieve stability in all operating conditions, and at the same time have a transient response fast enough to satisfy the specifications in FIKS. Traditional rules of thumb for stability were developed with larger power plants in mind and cannot be applied to Riksheim without considering elastic effects. Furthermore, it was concluded that the way the governor at Riksheim is programmed may be unfortunate in some operating conditions and create larger oscillations than necessary when responding to a disturbance.

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