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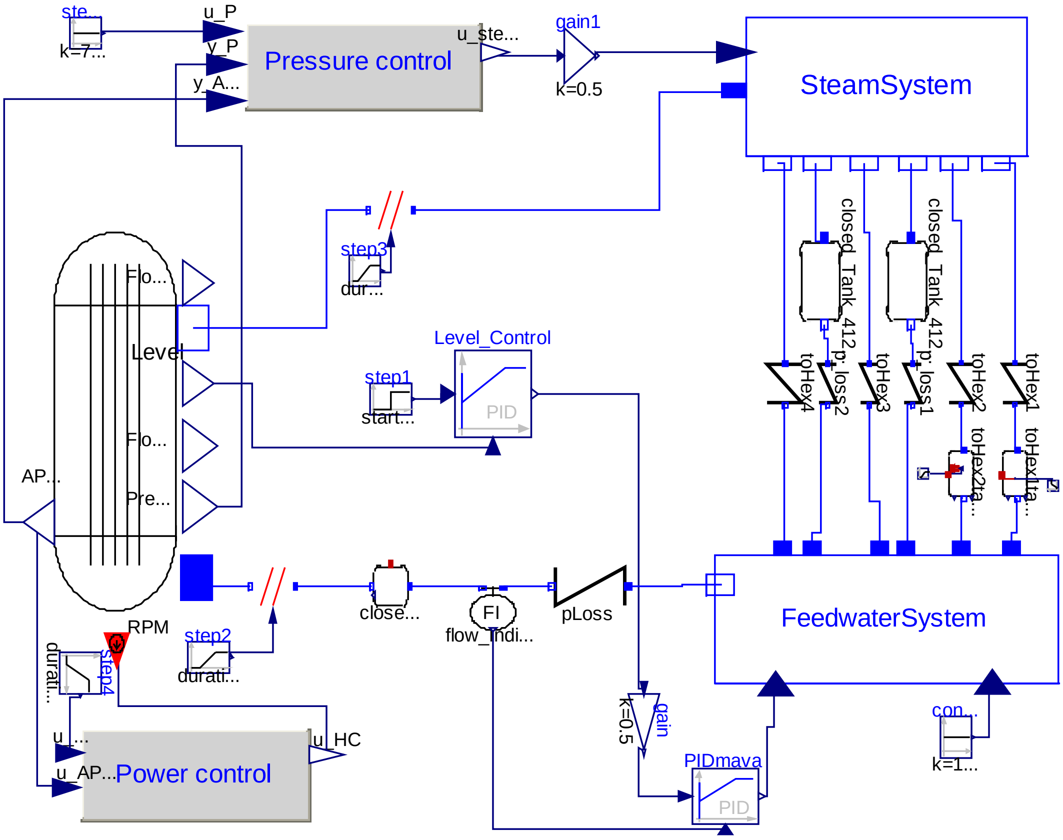

Modeling of the process system in a boiling water reactor

Master's thesis in Nuclear Engineering

OLLE PERSSON

Department of Applied Physics
Division of Nuclear Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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Master's thesis CTH-NT-265

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Cover: Printscreen from the whole model as it looks in *Dymola* (for details see chapter 4)

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Abstract

The subject of this master thesis is modeling of the process system in a boiling water reactor, and in particular Ringhals 1. The modeling is done in *Dymola 6.1.* The main reason for the project is that *Solvina AB* would like to examine the possibilities for simulating the entire system around the reactor, including steam system, turbines, pre-heaters and the feedwater pumps. The ultimate goal for the project was to have a working model for the entire BWR-system which responds realistically to a large transient for which measurement data are available. This goal was only reached partially, like the transient could not be implemented in a satisfying way mainly due to computational issues. The model was calibrated against a full power case, and verified against a case with a reduced power and some other circumstances with good results. A small transient was also introduced in the model to show that such a transient can be handled it in a realistic way.

Keywords: Modeling, Boiling water reactor, BWR, Ringhals, Dymola

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Nomenclature

Chapter 3.2

n	-	A neutron
^{B}Y	-	Nuclide Y with mass number B
ν	-	Number of created neutrons from fission event
k_∞	-	Infinite multiplication factor
f	-	Thermal utilization factor
ϵ	-	Fast fission factor
p	-	Resonance escape probability
ρ	-	Reactivity
t_d	s	Thermal diffusion time
Φ	$\mathrm{m^{-2}s^{-1}}$	Neutron flux density
L_T	m	Thermal diffusion length
$\mathbf{r}$	-	Vector in space
Σ_a	$\mathrm{m^{-1}}$	Macroscopic absorption crossection
β	-	Fraction of delayed neutrons
λ	$\mathrm{s^{-1}}$	Precursor decay constant
C	$\mathrm{m^{-3}}$	Precursor concentration
l	s	Prompt neutron lifetime

Chapter 3.3

$\dot{m}$	$\mathrm{kgs^{-1}}$	Mass flow into turbine stage
C_t	-	Stodola turbine constant
p_{in}	$\mathrm{Nm^{-2}}$	Pressure at inlet of stage
p_{out}	$\mathrm{Nm^{-2}}$	Pressure at outlet of stage
T_{in}	K	Temperature at inlet stage

Chapter 3.4

u	-	Output signal of regulator
K	-	Gain
e	-	Control error
T_i	s	Integration time
T_d	s	Derivative time

Chapter 3.5

$F(t, y, y')$	-	System of first order partial differential equations
y_n^m	-	Solution at point n in time and iteration m in the Newton method
Δt_n	s	Step length at point n
ρ	-	Convergence rate

Chapter 4.2

dP	$\mathrm{Nm^{-2}}$	Pressure drop over pipe
$\dot{m}$	$\mathrm{kgs^{-1}}$	Mass flow through pipe
C_1	$\mathrm{kg^{-1}m^{-1}}$	Flow constant
L_{pipe}	m	Effective pipe length
A_{pipe}	$\mathrm{m^2}$	Effective pipe area

Chapter 4.3

n	$\mathrm{m^{-3}}$	Neutron concentration
k_∞	-	Infinite multiplication factor
Φ	$\mathrm{m^{-2}s^{-1}}$	Neutron flux density
β	-	Fraction of delayed neutrons

λ	s^{-1}	Precursor decay constant
C	m^{-3}	Precursor concentration
γ	-	Diffusion parameter
Λ	s	Mean neutron generation time
l	s	Prompt neutron lifetime

Chapter 4.5

$\dot{Q}$	Js^{-1}	Heat flow rate
G	$kgK^{-1}s^{-3}$	Heat transfer coefficient
A	m^2	Conducting area
dT	K	Temperature difference

Chapter 4.7

dP	Nm^{-2}	Pressure drop over pump
n	rpm	Pump speed
n_{nom}	rpm	Nominal pump speed
V_{norm}	ms^{-1}	Flow constant
g	ms^{-2}	Gravity acceleration
ρ	kgm^{-3}	Fluid density

Chapter 4.8

$\dot{m}$	kgs^{-1}	Mass flow through valve
C_v	-	Valve sizing coefficient
N_6	-	Numerical constant (for changing units)
A_{open}	m^2	Area open to flow
F_p	-	Piping geometry factor
Y	-	Expansion factor
x	-	Ratio of pressure drop to upstream absolute static pressure
p_1	Nm^{-2}	Pressure at inlet
ρ	kgm^{-3}	Density at inlet

Chapter 4.9

$\dot{Q}$	Js^{-1}	Heat flow rate
A	m^2	Heat transfer area
T_{cold}	K	Temperature at inlet of tubeside
T_{hot}	K	Temperature at outlet of tubeside
T_{medium}	K	Temperature in medium at shellside
G_{cond}	$kg\ K^{-1}s^{-3}$	Heat transfer coefficient for condensating steam
G_{water}	$kg\ K^{-1}s^{-3}$	Heat transfer coefficient in the water
L	-	Relative water level on shell side

List of Figures

Chapter 1

Introduction

The subject of this master thesis is the modeling of the process system of a boiling water reactor, and in particular Ringhals 1. The main reason for the project is that *Solvina AB* would like to have a model that can simulate the entire system around the reactor, including steam system, turbines, pre-heaters and the feedwater pumps. There are already three separate models for these systems at *Solvina*. The advantage of a model of the entire system is that the control system can be implemented in a much more realistic way since all the parameters needed actually simulated in the same model. Otherwise responses from parts of the system that are are not modeled have to be introduced by other means as intelligent estimates. This is the case in three already existing models which are representing different parts of Ringhals1. These models were the starting point for this project and were used to get to know the system. Big parts of these models have also been used in the final model.

1.1 Purpose

The ultimate goal for this project is to have a working model for the entire BWR-system which responds realistically to a perturbation. If that goal is reached the next task is to enhance the control system to better match the reality and to find possible enhancements in the process system. There are also improvements that need to be done in some parts of the model besides connecting them to each other. All the models also need more and better verification against real measurement data. There is fortunately some new data from Ringhals 1 where the reactor has been running at steady conditions at 65 percent power, and also some data from a transient. Attempts will be done to recreate this transient in the model and see whether it responds realistically. It is also possible to retrieve data directly from the power plant, the temperature and pressure as well as other quantities are continuously measured at different points in the system, the sampling rate is though rather low.

1.2 Method

The modeling will be done in a *Dymola 6.1* which is an object oriented software based on the programming language Modelica. *Dymola* is widely used at *Solvina* and there is a lot of knowledge about it there. *Solvina* has developed a special library of components for handling fluid mechanics, and especially two-phase flows. These valves, pipes, pumps etc. are the base for the three old models and will also be the base for this master thesis.

1.3 Background

There have been three separate projects before this master thesis dealing with the BWR-system at Ringhals. None of the models are of course perfect and there are a lot of things to be improved to make them more realistic. There is one model for the steam-system, it describes the system from the containment wall to the entrance of the condenser. The second model is the reactor and control system for the feedwater pumps, the feed water system in this model is however very simplified and the focus is controlling the frequency of the pumps. The third model is the feedwater system and the pre-heaters. Details about the previous models are reported in section 2.2.

1.4 Limitations

It is only the main process that has been considered in this thesis, that is the flow from the condenser to the reactor and back to the condenser and the connections between the steam system and the pre-heaters. Special safety systems have not been considered. To reduce the complexity and the number of equations in the model only one of the two turbine branches have been modeled. The models will be kept as simple as possible to get the model to converge within a reasonable time.

Chapter 2

Nuclear power and background

2.1 Ringhals 1 - Description

There are four nuclear reactors located at Ringhals near Väröbacka 60 kilometers south of Göteborg. Three of them are pressurized water reactors but Ringhals 1 is a boiling water reactor. The construction of Ringhals 1 started in the year 1969 and the electricity production started 1976. [1]

A nuclear power plant is very complex, there are a lot of pipes, valves and control systems that are necessary to run and control the reactor and the turbines. In addition there are lots of systems guaranteeing the safety of the plant, all of these are very important even though they hopefully will not be used. Figure 2.1 shows pretty much what this thesis is about, namely the flows, temperatures and pressures in the process system. Note especially the six connections from the steam system to the feedwater system where the hot steam or liquid is used for heating in the preheaters. The generator load is 451 MW and the reactor power is at 110 %, i.e about 2500 MW.[28] The only difference between for example a coal-fired power plant and a nuclear power plant is the way the water is heated and boiled to steam. The turbine systems and the generator are very similar. The preheaters are using steam from the turbines to heat the feedwater to 173 °C, the reason is to increase the efficiency of the power plant.

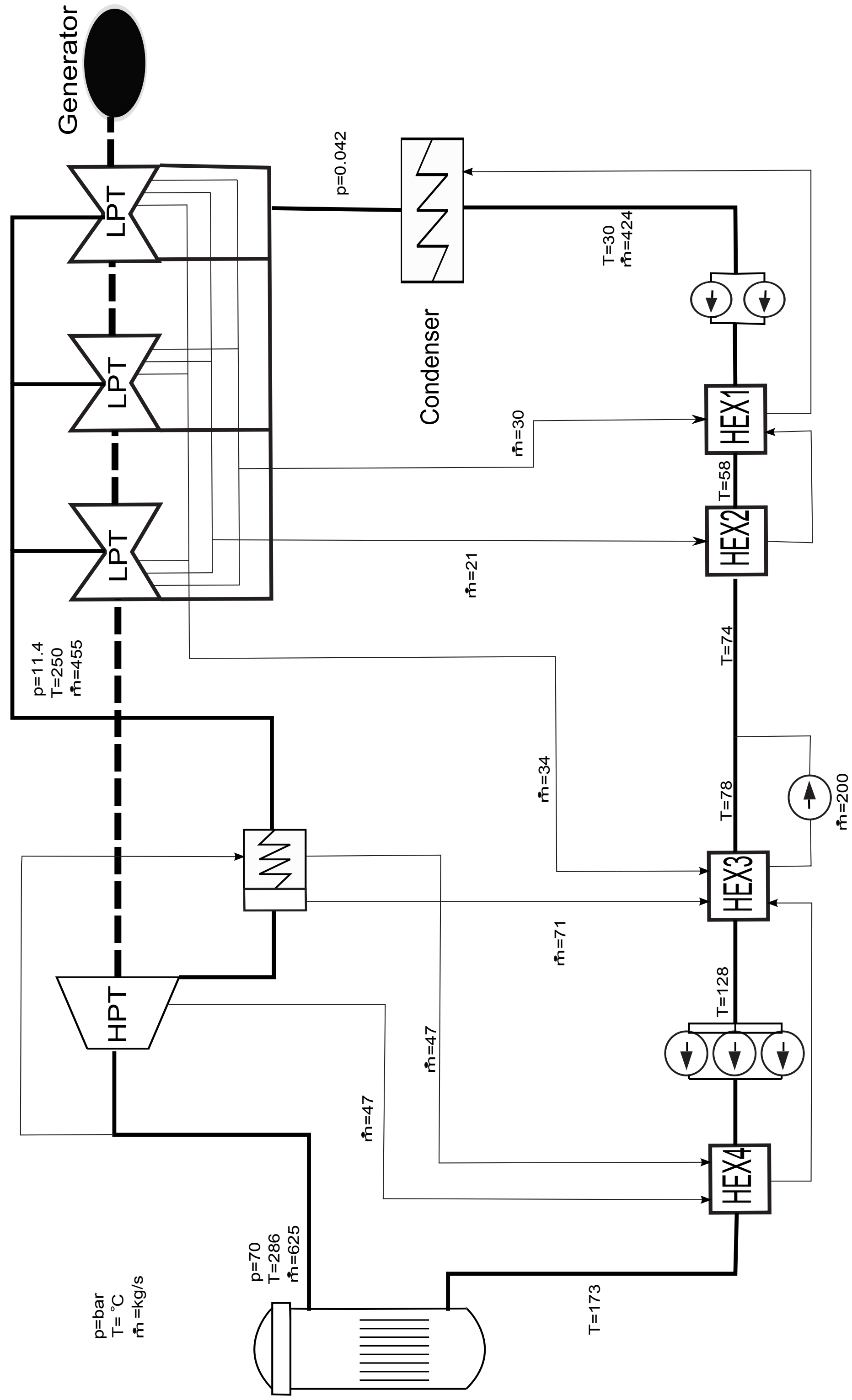


Figure 2.1: *Process system at Ringhals 1*

2.1.1 Reactor

The purpose of this section is to describe the flows in the reactor, the fission and the neutronics in the reactor are explained in the theory section 3.2. The flows in and around in the reactor are quite complex. The flow into the reactor from the two feedwater systems is at normal conditions about 1256 kg/s, see figure 2.2. The pressure and temperature at this point are about 70 bar and 173 ℃. The feedwaterflow mixes with the recirculation flow in the downcomer and continues to the lower plenum through the recirculation pumps. The temperature of the water in the lower plenum is 273 ℃. There are 6 circulation pumps which circulate the flow in the reactor. The flow rate through the reactor is huge, but it is needed so that the core were the fission creates a lot of energy can be cooled. [26]

The water then flows from the lower plenum through the reactor core where the water starts to boil at 286 ℃ after about half a meter. The steam is very moisty when it reaches the top of the core and less than 10 % of the mass flow remains after the steam and moisture separators in the top of the reactor the rest has been separated. The separated water is then again mixed with the incoming feedwater in the downcomer. The thermal effect of the reactor core is 2540 MW at maximal reactor effect which is 111.89%. [28] The total height of the reactor pressure vessel are 20 meters and the diameter is about 6 meters. [26]

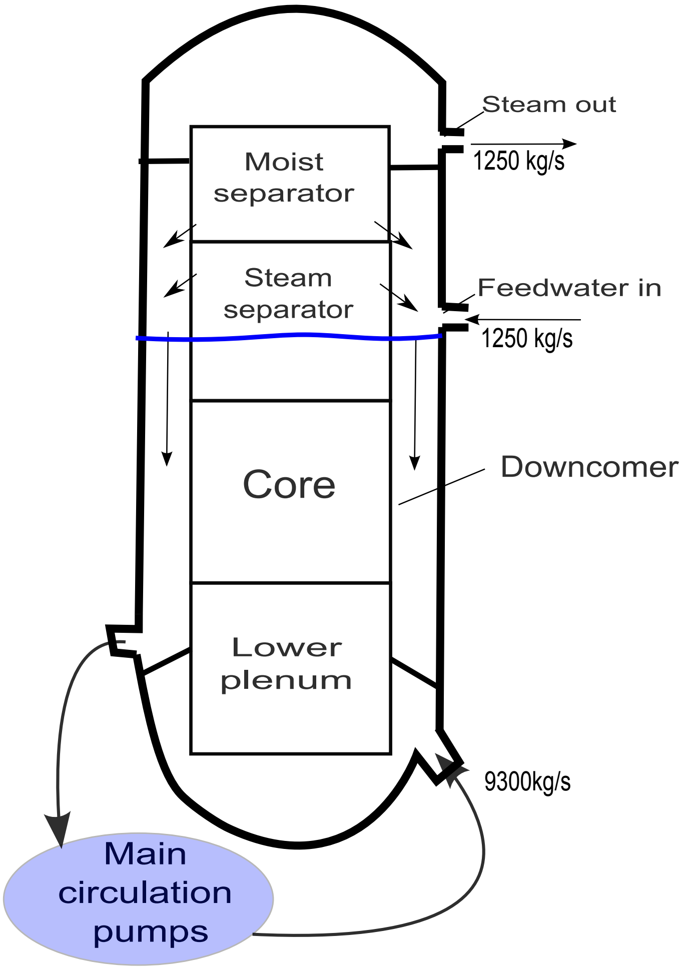


Figure 2.2: *Flows in the reactor pressure vessel [28]*

The core The fuel in Swedish nuclear reactor is made of uranium which is enriched from 0.7 % of the U-235 isotope to somewhere around 3%. The fuel pins in the reactor core have a diameter of about 1 cm and are surrounded by a zircaloy-cladding. These fuel pins are configured into fuel elements and the height of the core is 4 meters. [26] The core consists of 648 fuel elements and 157 control rods. Control rods are one of the means for controlling the reactor power. [2]

2.1.2 Steam system

The schematics of the important parts in the steam system can be seen in figure 2.3, each part of the system are explained in the following paragraphs.

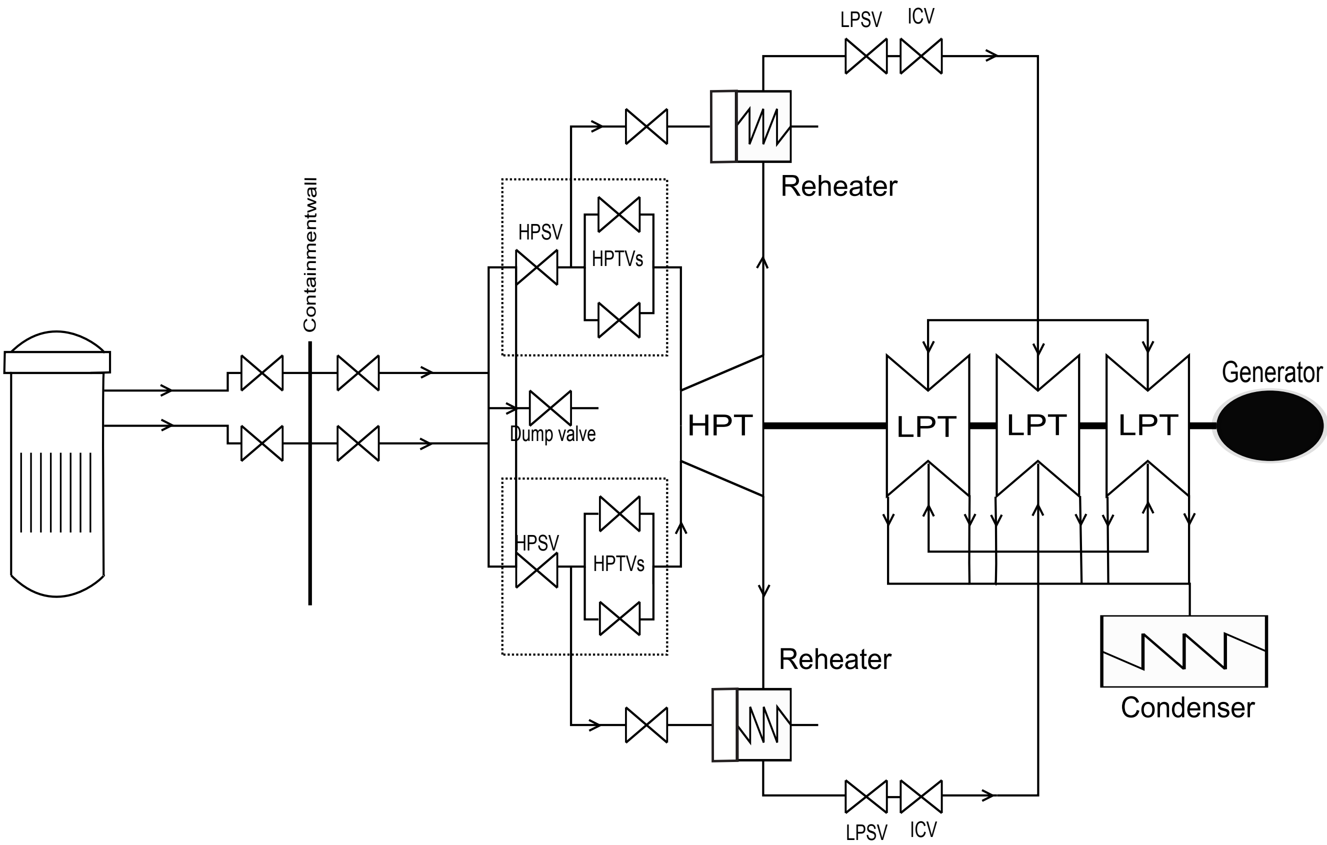


Figure 2.3: *Schematics of the steam process system, the dotted lines denote the two high pressure steam chests.*

Main steam pipes The dry steam that comes from the reactor is transported through eight pipes which are merged to four before leaving the containment. There are valves both inside and outside of the containment-wall, and the purpose of these is to isolate the containment from the vicinity in case of a severe accident. Then two pipes are going to each turbine system. Some of the steam is also taken to other parts of the system, for example the pressure relief system that in some cases controls the reactor pressure or during start up when fresh steam is used directly in the pre-heaters. [28]

Steam dump The purpose of the steam dump system is to have a way to be able to get rid of auxiliary steam from the reactor to avoid a too high reactor pressure. The steam is dumped to the condenser instead of passing through the turbines. This represents lost energy but it might be necessary to dump the steam if the reactor power is too large compared with the generator load. The steam dump valves are continuously used for controlling the reactor pressure when the turbines cannot handle it on their own.

High pressure steam chest There are two high pressure steam chests, one for each pipe coming from the containment. Each of them consists of a High Pressure Safety Valve (HPSV) and two High Pressure Throttle Valves (HPTV). There is steam taken to the two reheater systems between the HPSV and HPTV:s. The purpose of the HPSV is to shut down the steamflow to the turbines in case of some failure and redirect the flow through the dump valve which is opening when the HPSV:s are closing. The HPSV are fully opened when the power plant runs normally. The purpose of the HPTV:s is to control the steamflow to the turbines so they can keep the desired turbine frequency under their current load. The HPTV:s are almost fully open during full power conditions, they can also be used as a backup in case of a malfunction in the HPSV:s.

High Pressure Turbine (HPT) Each of the two turbine systems contains one high pressure turbine and three low pressure turbines. These four turbines are coupled to the same axis and generator. The desired frequency of the axis is 3000 rpm and the maximum power output for each generator is about 450 MW.

The pressure of the steam drops from 70 bar to about 63 bar as the steam travels from the reactor to the inlet of the HPT and the temperature drops from 286 ℃ to 278 ℃. The turbine consists of 6 steps and there is some steam taken after the fifth step to heat the feedwater in the preheater number 4, see chapter 2.1.3. The HPT is responsible for about one third of the total power output, and the pressure and temperature after the turbine is roughly 11.2 bar and 185 ℃ respectively. [28]

Reheater system About 23 kg/s of hot steam is taken from each of the two high pressure steam chests to the hot tube side of the reheaters. The purpose of this system is to heat and dry the moist steam after the HPT which now contains about 14 % of moisture. The lower part of the reheater is a moisture separator and the condensate from there is transported to the separator drainage tank. The condensate flow to this tank is about 70 kg/s and is eventually used to heat the feedwater in the preheater 3. The steam is almost completely dry after the moist separation and are ready to be reheated from 185 ℃ to 250 ℃ by the hot steam from the high pressure steam chests. The steam from the hot tube side is after the reheater transported to another drainage tank and is also eventually used for the preheaters in the feedwatersystem.

The reason for drying and reheating the steam is to increase the turbine efficiency and to not have water drops condensating in the turbines. Drops can cause corrosion and also damage the turbines.

The reheated steam goes to the low pressure steam chests which consist of a low pressure safety valve (LPSV) and an intercept valve (ICV). The purpose of these valves is to shut down the flow to the low pressure turbines in case of some kind of malfunction.

Low Pressure Turbine (LPT) and condenser There are three LPT:s which are delivering the other two thirds of the total power. The pressure and temperature drops from about 10-11 bar to 0.04 bar and the temperature from 250 ℃ to 29 ℃. Each LPT consists of eight steps and there are steam exhausts to the preheaters after step three, six and seven. The outlet of each turbine is connected to the condenser which is cooled by seawater. Note that the pressure in the condenser is very low, only 0.04 bar. Incondensable gases are constantly sucked out by ejectors to keep this low pressure. The cooling water is taken from the sea and the flow rate is 22 m^3 per second per condenser. [2]

2.1.3 Feedwater system

The main parts of the feedwater system are 4 heatexchangers, one condensate pump-block and one feedwater pump-block. All the heatexhangers have steam inlets to the shellside of the exhangers from the turbines. The steam to the heatexchanger 4 (HEX4) comes from the fifth step of the high pressure turbine and the steam to heatexchangers 3,2 and 1 comes from the 3rd, 6th and 7th step of the low pressure turbine respectively. All the heatexchangers except the second one do also have an inlet for hot liquid. The hot liquid to HEX4 is the condensate from the moist separator in the reheater system, and has travelled through the drainage tank. The condensate from HEX4 goes into the liquid port of HEX3 and similarly the condensate from HEX2 goes to HEX1. The liquid inlet to HEX3 also comes from the separated water in the steam separator after the high pressure turbine. The flows around the heat exchangers can be seen in figure 2.1 for 110 % reactor power and 100 % turbine load.

The condensate from HEX1 goes to the condenser. The condensate from HEX3 is actually pumped into the feedwater, about one third of the mass flow into the reactor comes from this source. This makes HEX3 harder to model and control compared with the other heat exchangers.

There are three important valves in the feedwater system process. One bypass valve with the purpose to bypass some flow pass HEX1 and HEX2. The bypass valve starts to open when the flow on the tubeside of HEX1 exceeds 450 kg/s. There are also a main-valve which normally is fully open and one control valve which controls the flow into the reactor, these two valves are positioned at the end of the feedwater system after HEX4.

The condensate pump-block consists of two pumps, but only one of them are running during normal circumstances. In the same way does the feedwater pump-block consist of three pumps and two of them are normally running. Which pumps are running varies because the pumps should be worn equally much.

There is also a small system which is for cleaning the feedwater before it enters the reactor. The unwanted substances comes for example from corrosion and leakage of cooling water in the condenser. [27]

2.2 Previous models

There have been three separate projects before this master thesis dealing with the BWR-system. Together they describe more or less the entire main loop of the coolant at Ringhals 1. There are however a lot of boundary conditions that can be replaced by better models. There is also a need for better simulation of the control systems, because parts in the different models are influencing each other.

2.2.1 Reactor

This model originates from a master thesis written in 2007 [11]. The focus was mainly to develop a model for the reactor. This was done by describing the neutronics with the point kinetic equation with six groups of delayed neutrons, the feedback effects from void, moderator density and the doppler effect were also taken into account, see section 3.2.2 for more information about feedback effects. The control rods are however not taken into account in this model and hence the reactor power is controlled only by the main feedwater pumps.
The core is modeled as several tanks from the bottom to the top, where the total volume of the tank equals the core volume. There are mass and energy balance equations for the flow between the different tanks representing a segment of the core. The thermo dynamical properties of each tank are used to calculate the reactivity and the neutronics, these calculations result in a generated heat in each tank. The moisture and steam separators and downcomer were modeled as one component. There is also a simple model for the feedwater system. Since there is another model for the feedwater system which describes primarily the heat exchangers much better, the feedwater model from this project has not been used. Control systems for the feedwater pumps, the main circulation pumps and the reactor pressure are also included. There is not much verification done for this model. The main reason for this was the lack of data. However, the stability of the model has been tested during different kinds of transients, such as step changes in the reactor level.
There are some problems with stiffness discovered when the models were running for a long time, for more information on stiffness see section 3.6. This stiffness appears after a long time of stability and is therefore acceptable because if one introduces an earlier transient the problem will not appear. The problem can however be a bigger issue when other models are connected to the reactor. There are some initiating transients that take about 100 seconds before they die out and the system becomes stable. The reactor is optimized for a power level of 110 % which means a steam flow out of the containment of 574 kg/s to each of the turbine branches.

2.2.2 Steam system

This model is also a result of a master thesis, but written in 2011 [21]. The structure is easy to understand and there were test cases for the transients and turbine trips mentioned in the report. It describes the system from the containment wall to the entrance of the condenser. Besides these boundaries there are also boundary conditions needed for the steam dump system, the steam extraction from the turbines and the reheater tube side. There is also a control system which controls all the valves in the steam system.
The control system consists of four parts. One rotational/speed-controller for the turbines. Since the generator is not modeled the frequency of the turbine is calculated in a simplified way which gives a value to work with. The setsignal is 3000 rpm and if the frequency exceeds 3300 rpm the turbine is shutdown, i.e the HPSV and LPSV are closed and the dumpvalves are opened. The second and third control systems regulate the pressure in the reactor tank by closing and opening the HPTV and dump valve. The fourth system is not a real control system, but is there to provide a more realistic flow through the reheaters.
The calibration of the model has been done according to the pressure and temperature drop through the system at full power. Then the model is verified against reduced power and a turbine trip with reasonably good results. The author is well aware of the shortcomings of the model, and one of them is that the turbine has no inertia, i.e the calculation of the turbine frequency does not depend on the previous frequency and the acceleration may be unreasonably high. Also the turbine should not be able to accelerate when the generator is connected to the grid, but the generator is not modeled. Future are improvements mentioned below:

- More verification and improvements of regulators.
- Improving of the reheater-system to better fit the real behavior.
- A better turbine-model with generator switch.

There are some rather large initiating transients in the beginning of this model, especially in the pressure. But they die out very quickly and are more or less gone after 20 seconds. This model has problems with handling flows of steam below 600 kg/s, the main reason for this is that there is no control system for the generator load.

2.2.3 Heat exchangers and feedwater system

This project is an internal project at Solvina and has no real report connected to it. It is however very well-structured but still a bit hard to understand without any documentation. The model describes what happens from the condenser to the reactor. The main parts are the two condensate pumps, the four heat exchangers and the three feedwater pumps and also the valves mentioned before. There are four additional boundary conditions for the hot steam coming to the heat exchangers from the different turbine-steps, and also two boundary conditions after HEX 2 and HEX 4 for the cascade coupling to HEX 1 and 3. None of the heat exchangers are modeled in exactly the same way, and especially HEX 3 is more complex than the others. This is due to that the condensate of this heat exchanger is pumped into the feedwater flow. The control system provided in this model consisted of 3 main parts:

- PI-regulators that controls the level in the heat exchangers.
- An extra control system for the additional pumps and valves in HEX3.
- A PI–regulator for the by-pass valve of the two first heat exchangers that depends on the condensate flow.

The focus of this model seems to have been to model the temperature rise of the feedwater flow and the heat exchanger levels in a realistic way. The mass flows from the steam exhausts of the turbines into the shellside of the heatexhangers are though not calibrated to reality, which makes this work a bit harder.

Chapter 3

Theory

3.1 Water phase theory

The water in a boiling water reactor changes phase several times while it is traveling through the process system. A simple phase diagram for water can be seen in figure 3.1. Note that the melting curve between the solid and liquid region lean a bit to the left because water is contracting while melting. [16] The two points marked on the pressure vapor curve are the points for the state of the fluid after the steam separators in the reactor and in the condensor.

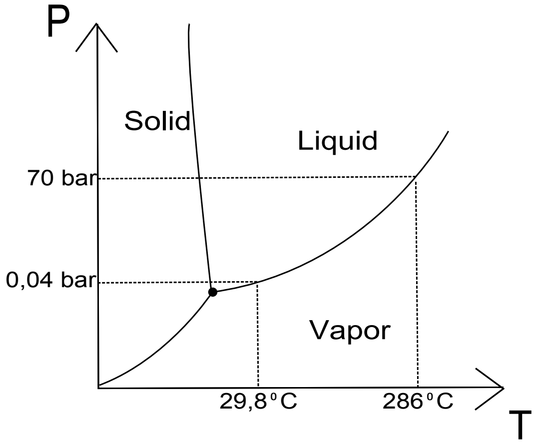


Figure 3.1: *Phase diagram for water, with two important point in the process system at Ringhals 1 [13]*

3.2 Fission and reactor theory

Fission is a general concept when a atomic nucleus is split into two lighter ones. In a nuclear reactor the the main source of energy comes from neutrons splitting the Uranium-235-isotope. But there are also energy coming from fission of other nuclides which are formed during a fuel cycle such as Plutonium-239. The energy released in a fission is due to that the sum of the mass of the products is less than the total mass before the reaction. Each fission releases about 200 MeV.

The general reaction of a fission of U-235 can be seen in eq. (3.1).

$$n +^{235} U \longrightarrow \quad ^{B}Y +^{236-B-\nu} Z + \nu n \tag{3.1}$$

ν is the number of released neutrons of the fission, which on average is around 2.4, these neutrons are called prompt neutrons. Most of the energy released becomes kinetic energy of the products but some of the energy also goes to emission of gamma rays. A very important phenomena in a nuclear reactor corresponds to the delayed neutrons, as a matter of fact the reactor would be very hard to control without these neutrons which are released a while after the fission event. These neutrons originates from β-decays of the lighter nuclides Y and Z formed in the fission. The neutron cycle time, i.e the time needed for one neutron to slow down and induce a fission and create new free neutrons, would be very small without the delayed neutrons, around 0.1 ms [22]. This would mean that the reactor would be very hard to control, but fortunately the delayed neutrons increases the neutron cycle time to about 0.1 s. The fraction of delayed neutrons for a U-235 core is about 0.65 %.

What happens when a neutron is approaching a nucleus is very much dependent of how much kinetic energy the neutron has. There are basically three different things that can happen, scattering, capture or fission. The probability for what happens is called cross-section and has the dimension of an area, an example of a cross section can be seen in figure 3.2, which shows the capture cross section for U-238. Note that there are huge resonance peaks between 10 and 10000 eV. It is important to avoid these as much as possible in order to have a good neutron economy in the reactor [5]. A general rule for neutron interaction is that the probability for interaction is higher for slow neutrons. This is in particular true for the fission of U-235. The initial energy of the neutrons after a fission is very high, and therefore the neutrons have to be slowed down in order to induce new fissions. This slowing down process is called moderation and is done by the water in a light water reactor like Ringhals 1.

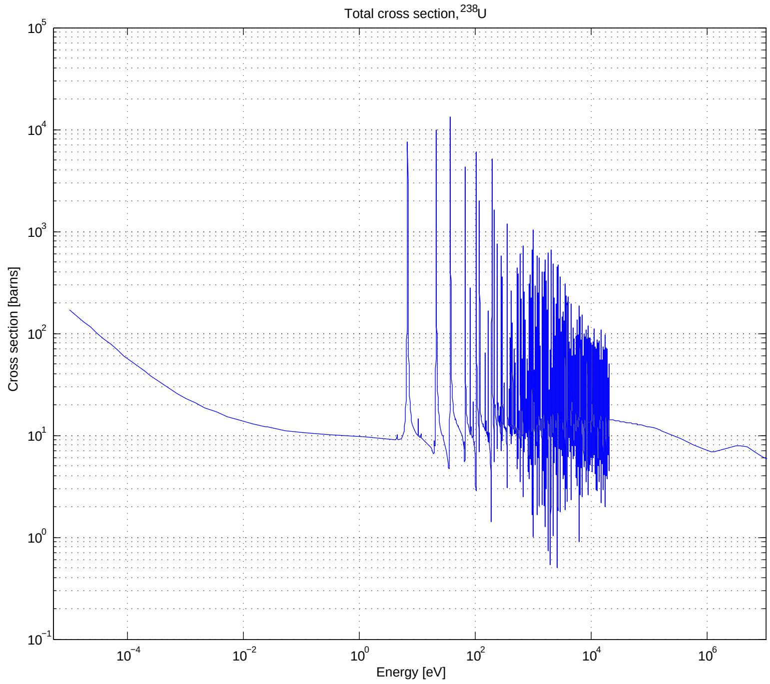


Figure 3.2: *Total cross-section of* ^{238}U*, (barn* $= 10^{-28}m^2$*) [13]*

3.2.1 The four-factor formula

The most common and simple way of describing the neutron economy in a reactor is by the four-factor formula, eq. (3.2). The formula is a good tool for understanding the basic phenomena regarding the neutronics in a thermal nuclear reactor.

$$k_\infty = \eta \epsilon p f \tag{3.2}$$

k_∞ **is the infinite multiplication factor**. The multiplication factor is a measure of how many neutrons there are in any neutron generation and the preceding generation. That is, $k > 1$ means a growing neutron population and vice versa. The subscript ∞ indicates that leakage of neutrons from the reactor is not taken into account.

f **is the thermal utilization factor,** it is defined as the ratio between the number of thermal neutrons absorbed in the fuel and the number of neutrons absorbed totally in the core, i.e in fuel, water and structure.

η **is the thermal fission factor**, it is basically the ratio between the number of created neutrons and absorbed neutrons in the fuel.

ϵ **is the fast fission factor**, it takes into account the fission that is caused by fast neutrons. This is the only one of the four factors that is greater than unity.

p **is the resonance escape probability**, it is the probability for fast neutrons to slow down and not be absorbed in the resonances in U-238, see figure 3.2. [5]

3.2.2 Reactivity and feedback effects

The reactivity of the reactor is defined as:

$$\rho = \frac{k-1}{k} \tag{3.3}$$

When the reactivity is zero the reactor is stable. If $\rho > 0$ the reactor is super critical, i.e the power is increasing, the opposite is called sub-critical. The reactor becomes prompt super critical when $\rho > 0.0065$ because then the reactor is critical without the delayed neutrons and the power is increasing very rapidly.

There are four main phenomena that affect the reactivity which all are very important to think about when controlling and modeling a nuclear reactor. The most obvious one is the position of the control rods. The rods are put a bit into the core in the beginning of a fuel cycle to lower the reactivity when the fuel is fresh and the enrichment is high. The control rods are fully withdrawn in the end of the cycle. The other three phenomena are negative feedback effects.

The fastest one of these effects is the doppler effect. The reason for this effect is the doppler broadening of the resonance-peaks in the cross-section for the U-238 isotope. It is closely related to the p-factor in the four-factor formula. The second effect is the moderator temperature, a higher temperature means a lower density of the water and therefore a poorer moderation. The third effect is the void-fraction, more void in the core means poorer moderation. All three of these effects are very much alike, an increase in power gives an increase in temperature which lowers the reactivity and the power becomes stable again. The main difference between the three feedback effects is the timescale.

3.2.3 Point kinetic model

The point kinetic equations can be derived from the time dependent diffusion equation for thermal neutrons, which can be seen in eq. (3.4) [14].

$$t_d \frac{\partial \Phi(\mathbf{r}, t)}{\partial t} = L_T^2 \nabla^2 \Phi(\mathbf{r}, t) - \phi(\mathbf{r}, t) + \frac{s(\mathbf{r}, t)}{\Sigma_a} \tag{3.4}$$

This is an ordinary diffusion equation and the terms on the right hand side refers to transport of neutrons, absorption and a source. The equation can be derived from transport theory with some approximations, for example Ficks law. The main approximation from diffusion theory to the point kinetic model is that the reactor is seen as homogeneous, (as one point), i.e the space dependence is removed. Equation (3.4) then becomes:

$$t_d \frac{\partial \Phi(t)}{\partial t} = -\Phi(t) + \frac{s(t)}{\Sigma_a} \tag{3.5}$$

The source of neutrons consists of two parts, one from prompt neutrons and one from delayed neutrons. This means that the source term can be written, using k_∞ and p from the four-factor formula, as eq. (3.6).

$$s(t) = \left[(1 - \beta)k_\infty - 1\right] \Sigma_a \Phi(t) + p \sum_{i=1}^{6} \lambda_i C_i(t) \tag{3.6}$$

The resonance escape probability can be approximated to unity if one assumes that all neutrons have the same average neutron energy. Using eq. (3.6) in eq. (3.5) and the fact that the thermal diffusion time t_d is almost the same as the prompt neutron life time l in thermal reactors give eq. (3.7) which is the point kinetic equation.

$$\frac{\partial \Phi(t)}{\partial t} = \frac{\left[(1 - \beta)k_\infty - 1\right] \Phi(t)}{l} + \frac{1}{l\Sigma_a} \sum_{i=1}^{6} \lambda_i C_i(t) \tag{3.7}$$

The six equations for the neutron precursors are just first order ordinary differential equations in time. The change in the precursor concentration depends on the source, which is proportional to the neutron flux, and the decay rate, which is proportional to the precursor concentration itself. Hence we get eq. (3.8) for the precursors.

$$\frac{dC_i(t)}{dt} = \beta_i k_\infty \Sigma_a \Phi(t) - \lambda_i C_i(t) \tag{3.8}$$

Equation (3.7) toghether with eq. (3.8) forms a system of 7 time dependent differential equations which can be solved quite easily if the governing parameters are known.

3.3 Turbine theory

There are a lot of different theories describing how a turbine works, one of them is called the Stodola Turbine theory and was invented by Aurel Stodola in 1927. The main equation in this theory relates the mass flow to the inlet temperature, and the pressure at the inlet and the outlet, see eq. (3.9).

$$\dot{m} = C_t \frac{p_{in}}{\sqrt{T_{in}}} \sqrt{1 - \left(\frac{p_{out}}{p_{in}}\right)^2} \tag{3.9}$$

C_t is the Stodola turbine constant and is a measure of the effective flow area through the turbine. The power of the turbine stage can then be calculated from the difference in energy flow. [3]

3.4 Control theory

There are a lot of control systems in every process industry, and also in a nuclear power plant. One of the most common regulators used is the PID-controller which is a kind of feed-back control. The PID controller produces a control signal $u(t)$ depending on the control error $e(t)$ which is the difference between a reference signal $r(t)$ and the output signal $y(t)$ of the process which should be controlled, see eq. (3.10) and figure 3.3.

$$e(t) = r(t) - y(t) \tag{3.10}$$

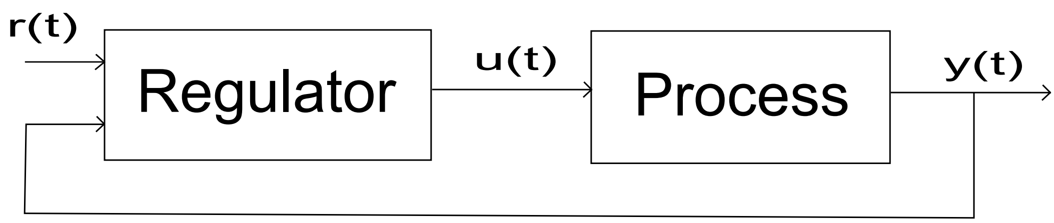


Figure 3.3: *Schematics of the basics for a regulator controlling a process*

The aim is to get the control error to be zero, this means that the output signal should be equal to the reference signal.

The PID-controller consist of three parts, one for each letter in PID. The first part is proportional to the control-error, the second is proportional to the integral of the control-error and the third one is proportional to the derivative of the control-error. The general formula can be seen in eq. (3.11). The purpose of the integral part is to avoid a stationary error. If the signal contains high frequency noise the derivative part will amplify this noise, and it is therefore recommended to have a low pass filter before a PID-regulator.[12]

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int e(t)dt + T_d\frac{de(t)}{dt}\right) \tag{3.11}$$

K is the gain of the controller, and a high K will give a fast controller. T_i and T_d are the integration time and derivative time and determines the importance of the I- and D-part. A lower T_i means that the control signal will change faster when the error is stationary. The derivative part predicts the error a time T_d forward in time, a larger T_d means that the output signal will change more rapidly when the derivative of the error is big. The three parameters have to be chosen carefully in order to get a regulator that controls the system in a satisfying way. There are several theories for how these parameters can be determined but no definite rules. The derivative part of the PID-controller is often proportional to $y(t)$ instead of $e(t)$ which can give a varying control-signal even if the control-error is constant. So called PI-regulators are also very common in the industry, and that is just a PID-regulator without the derivative part.

3.5 DASSL, DAE-solver

DASSL is the code used by *Dymola* for solving the equations in the system during this project. The main thing that distinguish DASSL from other solvers of differential equations is that the equations do not have to be written in standard form, see eq. (3.12), for DASSL to be able to handle them.

$$y' = f(t,y) \qquad y(t_0) = y_0 \tag{3.12}$$

The DASSL-code is made for solving equations looking like eq. (3.13) with intial conditions as eqs. (3.14) and (3.15), these problems are called *Differential Algebraic Equations* (DAE).

$$F(t, y, y') = 0 \tag{3.13}$$
$$y(t_0) = y_0 \tag{3.14}$$
$$y'(t_0) = y'_0 \tag{3.15}$$

Note that F, y and y' can be vectors and eqs. (3.13) to (3.15) forms a system of differential equations. This is a much more general way of writing differential equations and also the standard form in eq. (3.12) is included in eqs. (3.13) to (3.15). There are many advantages with solving the more general systems directly instead of converting the equations to standard form. The conversion might be very time-consuming and hard to do. There are even cases when it is impossible to convert the system to standard form, and other examples where it is very impractical in a numerical sense to solve the converted systems. [23]

The first step in the DASSL-code uses the kth order backward differencing formula to approximate the derivative. k can be any number between 1 and 5 and depends on the previous behaviour of the solution. Also the stepsize of the solver depends on the behavior of the solution. An approximation with $k = 1$ can be seen in eq. (3.16).

$$F(t_n, y_n, \frac{y_n - y_{n-1}}{\Delta t_n}) = 0 \tag{3.16}$$

This equation is solved by iterating according to eq. (3.17) which is called the Newton's method.

$$y_n^{m+1} = y_n^m - \left(\frac{\partial F}{\partial y'} + \frac{1}{\Delta t_n}\frac{\partial F}{\partial y}\right)^{-1} F(t_n, y_n^m, \frac{y_n^m - y_{n-1}}{\Delta t_n}) \tag{3.17}$$

DASSL is actually using a slightly modified version of Newtons method which solves eq. (3.16) even faster. The convergence rate is defined as:

$$\rho = \left(\frac{||y^{m+1} - y^m||}{||y^1 - y^0||}\right)^{1/m} \tag{3.18}$$

The norms in this equation is dependent on the error tolerances which is chosen in *Dymola*. The criteria for convergence is:

$$\frac{\rho}{1-\rho}||y^{m+1} - y^m|| < 0.3 \tag{3.19}$$

The Newton method ought to converge very rapidly and if convergence is not reached before $\rho > 0.9$ or $m > 4$ then the step size in time is reduced and the DASSL solver performs the backward differencing in eq. (3.16) again. When the newton method has converged to a new value of y this value have to be compared to the tolerance of the local error. If this condition is met, then the solver can proceed to the next time-step.

One of the disadvantages with DASSL is that initial conditions for both the function and the derivative must be given. These are not always known and DASSL must find some kind of guess for these values.[23]

3.6 Stiff problems

3.6.1 What is stiffness?

Stiff equations are equations that are hard to solve from a computational point of view [19]. There are equations which are easily solved analytically but at the same time hard to solve by computational methods. There is unfortunately not any stringent mathematical definition for stiffness, at least none that is widely accepted. One way of understanding the phenomena of stiffness is by studying the Jacobian matrix of the system. If the eigenvalues of the Jacobian differs a lot, the problem might be stiff. The big difference between the eigenvalues is equivalent to that the problem has solutions with timescales that differ a lot. Most attempts to define stiffness are in some way similar to eq. (3.20). A system of differential equations is said to be stiff over the interval $[t_0, t]$ if:

$$(t - t_0)min_j\big(Re(\lambda_j)\big) << -1 \tag{3.20}$$

Where $Re(\lambda_j)$ are real part of the the eigenvalues of the Jacobian matrix [10].

The stiffness of a problem is also affected by the timeframe which the problem is solved for [25]. The reason for this is that the size of the absolute values of the eigenvalues $|\lambda_{max}|$ should be compared to an inverse timescale. This means that the problem can easily be solved for 10 seconds, but convergence cannot be found if the problem is to be solved for 1000 seconds or more.

When solving a system of equations by a computational method that in some sense steps from y_n to y_{n+1} it is impossible not to make some kind of error. This means that other solutions have to be considered, even though they do not satisfy the initial condition, because the solver may happen to move from the exact solution to a nearby one. In some cases this can be catastrophic because it might be a fast diverging solution, and the solver will crash and fail to calculate the correct solution. When this happens, the problem is said to be stiff. Another important thing about stiffness in this thesis is that a problem may not be stiff during the initiating transients but becomes very stiff after a while when the initiating fast transients have died out. [24]
Another way of characterizing stiff problems is that an explicit solver such as *Euler Forward* becomes highly inefficient because the stepsize becomes very small to avoid the fast diverging nearby solutions. [10].

Let us consider a simple example where we have an ordinary differential equation in time:

$$\frac{d^2y(t)}{dt^2} = 100y(t) \tag{3.21}$$

which has the general solution:

$$y(t) = Ae^{-10t} + Be^{10t} \tag{3.22}$$

The coefficients A and B should be determined from two initial conditions:

$$y(t=0) = 1 \qquad \frac{dy(t=0)}{dt} = -10 \tag{3.23}$$

The very simple analytical solution to this problem is, $A = 1$ and $B = 0$:

$$y(t) = e^{-10t} \tag{3.24}$$

However when a computational method solves this problem there is always some error because the solver cannot have a infinetly small stepsize. This means that a very small fraction ϵ of the rapidly changing component of the general solution in eq. (3.22) will affect the final solution. The solution will numerically look like:

$$y(t) = Ae^{-10t} + \epsilon e^{10t} \tag{3.25}$$

Equation (3.25) becomes stable in time quite rapidly which results in an increase in step size for most numerical solvers. There is a risk that the solver will find a rapidly changing solution which is near the analytical one and the solver will crash. This means that the solution eventually will diverge if you integrate the problem long enough. [17]

3.6.2 Stiff Solvers

There are numerous different computational methods for solving differential equations. It is important to have an implicit solver when dealing with problems that might be expected to be stiff. One of the best of these solvers is the so called DASSL, which uses a backward differencing formula. DASSL is not the most efficient solver for non-stiff problem, but it has many advantages. One of them are that the DASSL-code can deal with differential algebraic equations without rewriting them to standard form. The DASSL-code is also heavily tested compared to other codes for example Radau IIa [9].

Chapter 4

Modeling

The purpose of this section is to describe how the components in the system have been modeled and mention the simplifications that have been made. All the modeling have been performed in *Dymola 6.1* which is an object-oriented software developed by *Dynasim* which uses the programming language *Modelica* for modeling the objects. The main feature of *Dymola* is that it can handle complex multi-engineering systems and that it is using automatic formula manipulation to avoid time consuming manual conversion of equations. [7]. Because of the graphical interface *Dymola* is especially good for modeling physical systems, because the models can look close to their true appearances, which makes the entire model easier to overlook.
Modelica is an object oriented language that has many similarities to more well known languages such as JAVA and C++. Each component in the system is generally represented by a model, and the information between the models are coupled with different types of connectors, such as real values or booleans. The models of similar kind can then be sorted into packages which makes the models easier to find. One of these packages is the *Modelica Standard Library* which contains other packages with components for mechanical, electrical, thermal systems etc. There is also a package for construction of control systems. All these basic components and standard packages are delivered with *Dymola*, so that a new user does not have to start from scratch in a new project.

4.1 General model structure in *Dymola*

More or less all of the *Dymola*-objects, called models, used in this project has a similar structure. There is a media package which is imported to all the components which handle water or steam. This package is used for calculating the unknown properties from the known ones, for example the temperature from the pressure and enthalpy. The components are connected by several different types of ports, the ones used for this master thesis are waterports and heatports and also ports for real values and booleans. All components with two waterports are also using a partial model called *PartialTwoPort* which redeclares the medium package in each port. Examples of two port components are tanks, pipes, valves etc. Some components do also have another partial model to take care of the initialisation of the component, this model is called *PartialMenuInitializationTwoPort*.

The media package used in this master thesis is WaterIF97. It is a high precision model for water when it is liquid, gas or multiple phases and follow the IAPWS/IF97 standards. The media package contains data for the pressure and temperure regions in figure 4.1. [8]

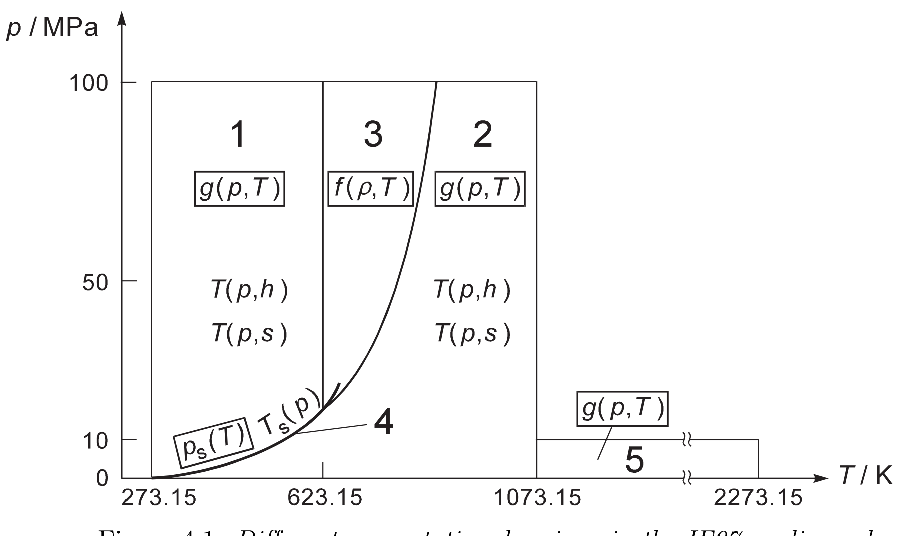


Figure 4.1: *Different computational regions in the IF97 media package*

The company Solvina AB has developed a library of components regarding fluid mechanics which is called the *Steam Power Library*. This library contains valves, pipes, tanks etc. that can handle both liquid and steam. A similarity between most of the components in the *Steam Power Library* is that reversed flow can be handled. This is done by making use of the *Modelica* function *semilinear(x,a,b)*. This function returns xa if $x > 0$ and xb if $x < 0$, and is used in the components as in eq. (4.1).

$$\text{port\_a.H\_flow} = \text{semiLinear}(\text{port\_a.m\_flow}, \text{port\_a.h}, \text{medium.h}); \tag{4.1}$$

This equation calculates the energy-flow in *port_a* from either the enthalpy in the port or from the medium in the component if the flow is reversed.

All the components with two or more waterports do also have an equation for conserving the mass by just setting the sum of the mass flows to zero. There is also a balance equation for the energy where also heat ports have to be taken into account. See eq. (4.2) for the mass and energy balances for a component with N waterports and M heatports.

$$\sum_{i=1}^{N} \text{waterPort\_j.m\_flow} = 0 \qquad \sum_{i=1}^{N} \text{waterPort\_j.H\_flow} + \sum_{j=1}^{M} \text{heatPort\_j.Q\_flow} = 0 \tag{4.2}$$

4.2 Pipes

The pipes in the nuclear power plant have been modeled either just by a simple pressure loss or by a static pipe coupled to a tank. The first case is much simpler and is used to shorten the simulation time and to be able to reach convergence. A simple pressure loss does however not model the dynamics very well and the delays of for example enthalpy changes in the systems is not considered. The main equation is however:

$$dP = C_1 \dot{m}|\dot{m}| + \frac{\partial \dot{m}}{\partial t} \frac{L_{pipe}}{A_{pipe}} \tag{4.3}$$

The pressure change is as can be seen proportional to the square of the massflow during steady state conditions and is affected by the dynamic term if the massflow is varying. This simple pressure loss model is found between the steam system and the feedwater system aswell as between the feedwater system and the reactor. The pressurelosses over the preheaters are also modeled in this simple manner. The pipes in the steam system is though modeled in a more complicated manner consisting of a pipe with a delay and a tank representing the volume of the pipe and therefore also the dynamics of the system better.

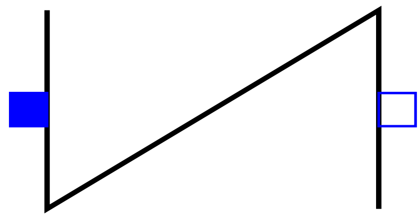


Figure 4.2: *A simple pressure loss*

4.3 Reactor core

The model of the core is basically split into two parts, one for describing the neutronics called the *reactor-model* and one for describing the flow through the core and the change in enthalpy called *tube-model*. The tube is divided into N regions, each with a corresponding port for heat flow. The neutronics is based on nominal values at 110% reactor power and 2500 MW thermal output. The neutron density in each region is calculated in the reactor-model using eq. (3.7) in the theory section, with a slight modification because of the multiple regions, see eq. (4.4). The neutron density n is used instead of the neutron flux Φ. These two properties are proportional to each other in a thermal reactor, because if one multiplies the neutron density ($[m^{-3}]$) with the neutron velocity one gets the neutron flux ($[m^{-2}s^{-1}]$).

$$\frac{dn_i}{dt} = \frac{k_{\infty,i}(t)(1-\beta) - 1}{l} n_i + \sum_{m=1}^{6} \lambda_{m,i} C_{m,i} + \sum_{j=1, j\neq i}^{N} \gamma_{ij} \frac{n_j}{l} \tag{4.4}$$

The extra term comes from the diffusion between the regions [20]. The importance of this diffusion is decided by the parameter γ and mean prompt neutron life time. Equation (4.4) is simplified to only contain one group of neutron precursors in order to to save computational time and a mean decay constant $\lambda_{mean} = 0.08$ has been used [6]. To simplify the model even further only the diffusion from the neighboring regions has been considered, this results in eq. (4.5) which has been implemented in the code.[11]

$$\frac{dn_i}{dt} = \frac{\rho_{tot,i} - \beta}{\Lambda} n_i + \lambda_{mean} C_i + \frac{\gamma}{l}(n_i - n_{i-1}) - \frac{\gamma}{l}(n_{i+1} - n_i) \tag{4.5}$$

Λ is the mean neutron generation time, defined as $\Lambda = l/k_{eff,i}$. The sum of the neutron-concentrations is scaled so that it is one at nominal conditions. This results in a heat flow into each region of the *tube-model* since the neutron density is directly proportional to the power. Changes in the heat flow results in temperature changes in the regions and therefore changes in the void-distribution. These quantities are used in the reactor-model for calculating the feedback from the moderator temperature and the void. The feedback from the Doppler effect is calculated from the neutron density. This is done because the temperature profile in the fuel is not considered in the model, but the temperature is proportional to the power and hence also the neutron density at stationary conditions. The formulas regarding the feedback effects can be seen in eqs. (4.6) to (4.9).

$$\rho_{tot,i} = \rho_{doppler,i} + \rho_{void,i} + \rho_{moderator,i} \tag{4.6}$$

$$\rho_{doppler,i} = k_{doppler}(n_i - 1) \tag{4.7}$$

$$\rho_{void,i} = k_{void}(\alpha_i - \alpha_{i0}) \tag{4.8}$$

$$\rho_{moderator,i} = k_{moderator}(T_i - T_{i0}) \tag{4.9}$$

The neutron precursors are modeled as in eq. (3.8), again with the simplification to only one group of neutron precursors. The equation implemented in the code for all the regions can be seen in eq. (4.10).

$$\frac{dC_i(t)}{dt} = \frac{\beta}{\Lambda} n_i - \lambda C_i \tag{4.10}$$

4.4 Downcomer and steam separator

The downcomer and steam separator are modeled as a single component. It is basically a simple tank with three waterports, one for the inflow of wet steam from the reactor, one outlet for the dry steam to the steam system and one for the water which is mixed with the feedwater and transported back to the main circulation pumps. It is important to have a stable water level in the downcomer at about 3.7 m above the reactor core, this is regulated by the feedwaterpumps. The water level is calculated by comparing the density of the steam and liquid, at present pressure, to the total density of the medium of the tank. The water level is considered when calculating the pressures at the ports of the downcomer. Since the feedwater flow is not connected directly to the downcomer the water level reacts a bit slowly to changes in the feedwater flow.
The quality of the steam at the outflow to the steam system has been set to 99%, the quality is in the real case very near 100%, but increasing the quality is causing problems in *Dymola*. The reason for this is that *Dymola* have a hard time deciding whether it is one or two-phase flow, since it is dry steam at the boiling point, see figure 3.1.

The liguid in the downcomer is transported to the main circulation pumps. There is though only one circulation pump in the model, and the flow is scaled to one sixth before the pumps and scaled back before entering the reactor.

4.5 Re-heaters

The re-heaters after the high-pressure turbine consists of one lower part which separates the water from the steam and one part that uses the fresh steam from the high pressure steam chest to heat the cold steam to a desired temperature, these two parts are completely separated in the model. The quality of the steam is again chosen to be 99% instead of 100% for the same reason as mentioned above. The separation part is just a pure separation by comparing the liquid enthalpy at current pressure with the actual enthalpy. The re-heating consists of a tube-side for the hot steam and a shell-side for the cold steam with a thermal conductance in between. The heat transfer depends on the temperature difference and the conducting area and the heat transfer coefficient as in eq. (4.11).

$$\dot{Q} = GA * dT \tag{4.11}$$

The aim for the rehaters is to heat and dry the steam from the high pressure turbine to 250 ℃. This is done by controlling the flow rate of the hot steam on the tube side of the re-heater with a PID-regulator. The regulator has the temperature after the re-heater as input-signal and controls flow on the tube side via a control-valve before the drainage tank.

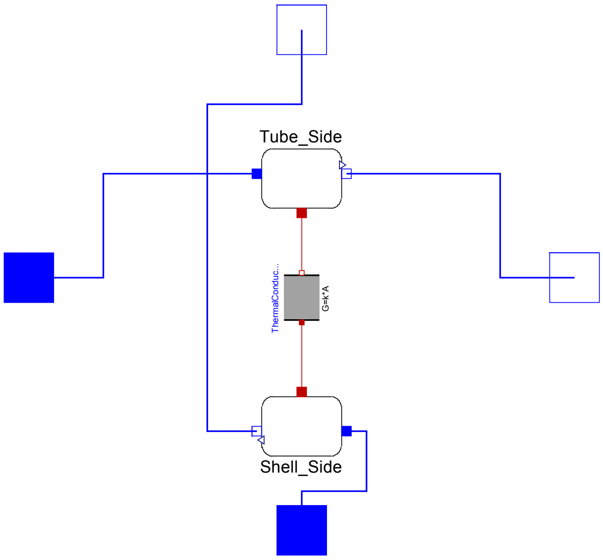


Figure 4.3: *Reheater model containing tanks with heat ports and a thermal conductance*

4.6 Turbines

Both the high pressure turbines and the low pressure turbines are based on Stodola's turbine theory and eq. (3.9). The models have though been simplified to minimize computational cost by putting steps together and just have a break where there is a steam exhaust. This means that the HPT:s first five steps are modeled by one Stodola-turbine and the sixth step is modeled by another one. The 8 steps in the LPT are modeled with four Stodola-turbines because of the three steam exhausts. A figure of the LPT-model can be seen in figure 4.4. Equation (3.9) is solved together with balance equations for the mass and finally the power output is calculated from the difference in energy flow. The three low pressure turbines are modeled as only one turbine, containing 4 Stodola turbine steps, which is scaled to handle the desired amount of flow.

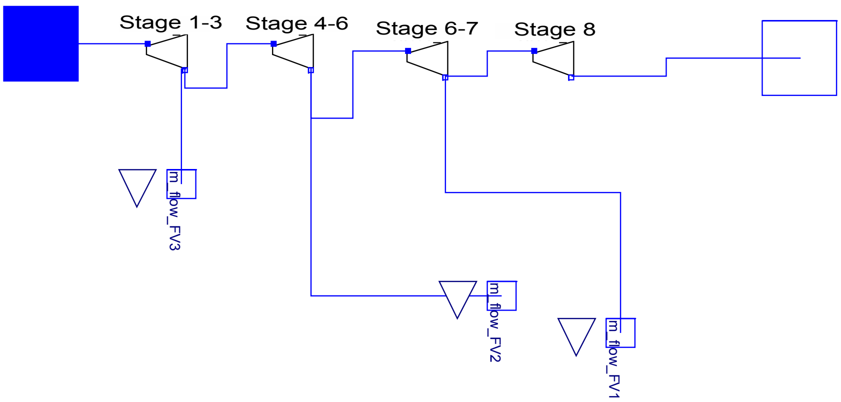


Figure 4.4: *Low pressure turbine model*

4.7 Pumps

The main equation of the pumps in the model is eq. (4.12).

$$dP = \left(\frac{n}{n_{nom}}\right)^2 f(V_{norm})g\rho \tag{4.12}$$

Where n is the speed of the pump and V_{norm} is the normalized speed of the flow with respect to n. The capacity of the pump is quadratically dependent on the pump speed. The function $f(\dot{V}_{norm})$ is the pump curve characteristics. The pump curve basically represents the height that the pump is able to push a fluid of a certain flow rate.

4.8 Valves

There are two different models for valves, the difference is that the valves in the steam system are able to handle choked flow whereas the valves in the feedwater system cannot. Choked flow is a phenomena which causes the velocity of the fluid to only depend on the upstream pressure and not on the downstream pressure. This might happen when the valve is closing or opening and the steam is accelerating rapidly and reaches the speed of sound. The equation for the mass flow for the more complicated valve can be seen in eq. (4.13) [15].

$$\dot{m} = C_v N_6 A_{open} F_p Y \sqrt{x p_1 \rho} \tag{4.13}$$

The constants before the square root are concerning different aspects of the valve, including the area that is open to the flow according to the valve characteristics (see the nomenclature for a short description of the constants). x is the pressure drop ratio and p_1 is the pressure at the inlet, this means that the mass flow rate is proportional to the square root of the pressure drop. The expansion factor Y is corrected if the pressure drop ratio is big enough for choked flow to occur.

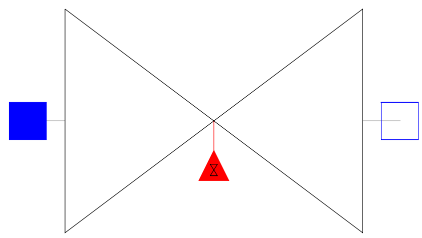


Figure 4.5: *The valve icon*

The valves for the condensate on the shell side of the preheaters have a very similar equation to eq. (4.13) but with a few less parameters. The old models contained valve actuators that simulated the opening and closing time for the valves, these have been removed in the new model to reduce computational time. The removal does not effect the properties of the system at steady state. The valves are now responding directly to the control signals without any delay.

4.9 Pre-heaters

The main part of the pre-heaters is a tank with two heat ports. The reason for the two heat port is that the heat flow is split into two parts, one in the beginning of the preheater when the feedwater is cold and one in the end when the feedwater is warmer with a pressure loss in between, see eqs. (4.14) and (4.15).

$$\dot{Q}_{cold} = \frac{A}{2}\Big[(T_{cold} - T_{medium}) * \big(G_{cond}(1-L) + L * G_{water}\big)\Big] \tag{4.14}$$

$$\dot{Q}_{hot} = \frac{A}{2}\Big[(T_{hot} - T_{medium}) * \big(G_{cond}(1-L) + L * G_{water}\big)\Big] \tag{4.15}$$

Where L is the relative water-level in the preheater. There are two different heat transfer coefficients G, one for the condensation of the steam and one for the heat transfer in the water. The control systems for the preheaters are PI-controllers regulating the steam flow through the preheater via a valve at the outflow of the condensate. $L = 0.4$ is the set-point for the PI-controllers. The level is calculated in the same manner as in the downcomer, i.e by comparing the densities of steam and liquid phases to the actual density in the tank. The inflows to the shell side of the pre-heaters were only modeled with a single flow in the old model, in reality there are several flows from different parts of the system. These flows have now been implemented and the parameters have been modified so that the pre-heaters work as expected.

4.10 Control systems

Besides the PI and PID-regulators for the preheater levels, the by-pass flow in the feedwater system and the reheater flow there are 4 main important control systems which have been modeled. The models are however not very realistic but very simplified, and there are several reasons for this. One is that it is hard to find information about the features of the control systems. The main reason is however that complex control systems tend to increase the simulation time a lot. Most of the control systems from the old models could therefore not be used. The main purpose of the control systems is to get the simulation running and to give reasonable feedbacks to perturbations in the system rather than representing the real systems exactly.

Downcomer water level control The aim is to keep the water level at 3.7 meters above the reactor core, this is done by two PID-regulators.The first one has 3.7 as set point and the level as measurement signal, the output is the desired feedwater flow. This signal is divided by two because of the two turbine branches. The second PID-regulator has the desired flowrate as setpoint and the actual flowrate as measurement signal and the output is the revolutions per minutes to the feedwater pumps. These two PID-regulators can be seen in the picture of the total model on the cover page.

Reactor power control The control rods are not modeled and the power is therefore regulated by the main circulation pumps. The current power level is filtered in a lowpass-filter and then compared with the actual power level. The speed of the pumps are increased if the power level is too low and vice versa. The reason that the pumps controls the power is because of the feedback effects mentioned in the theory section. A higher mass flow through the core means better cooling and lower temperatures which leads to a higher reactivity and power.

Reactor pressure control The pressure control system is modeled in two steps, the first step decides the desired outflow of steam and the second step regulates the dump valve and the HPTV:s. The inputs to the first step is the desired pressure, the actual pressure and the current power level. A higher power level generally means a larger desired outflow of steam. The desired flow rate is then divided by two for the same reason as above. The signal reaches a PID-regulator where it is compared with the actual flowrate and the position of the dump valve is changed accordingly. If the dump valve is completely closed and the pressure in the reactor is still too low the HPTVs also starts to close to regulate the pressure.

Turbine frequency control This control system is very simplified, mainly because of deficits in the models of the turbines and the generator. The purpose is to keep the rotational speed of the turbine axis at 3000 revolutions per minute. This is done by comparing the generator load and turbine power and adjusting the steam flowing to the turbines with the HPTVs. The main deficit of this control system is the frequency calculator which replaces the non existing model for the generator and calculates a frequency from generator load and turbine power. No account for turbine or generator inertia is taken into account and unreasonable accelerations can therefore occur. The turbines are tripped if the frequency exceeds 3300 revolutions per minute.

4.11 Simplifications

There was a huge need for simplifications in different parts of the model for many reasons. The most important one might be that the simulation time needs to be limited in order to make the model possible to work with and test different cases within a reasonable time frame. This was especially important when calibrating the entire model and lots of tests had to be made with various set-ups of parameters. Hence the complexity of the model was reduced and some deficits in the performance were accepted. A simpler system also means less variables to keep track of and less parameters to calibrate.

The second reason for reducing the complexity is the problem with stiffness. The model needs to be able to run a while after the initiating transients at stable conditions. After that one can introduce a transient anywhere in the system from these stable conditions.

Methods of analyzing and simplification

The task to eliminate stiffness is much harder than the task to reduce the time of simulation. Every simplification of the system, such as removing a pipe or a small tank will reduce the simulation time because there will

be fewer equations to solve. However it can still be tough to find good simplification that do not affect the performance of the model too much in comparison with the time gained. It is even harder to know which components or systems that need modification if the aim is to have a less stiff problem. One way of doing is to look at the eigenvalues of the problem and see which of them that differs a lot from the others. There is a possibility in *Dymola* to linearize the systems from stable conditions and then one can calculate the eigenvalues with MATLAB. The components which are causing the deviating eigenvalues can then be modified or even removed. Especially the removal of small tanks, made the system of equations easier to solve over a large time interval.
MATLAB can also be of great help in the analysis of the data. It is very inconvenient to search for problematic variables by just looking at the plots in *Dymola*. MATLAB has been very helpful with finding variables that have not reached stability or make unexpected jumps.
The best way to find some problematic parts of the model in *Dymola* is to let the debugger store the variables that have caused reduced step size or had a local error above 10 % most times during the simulation. Removing or simplifying the components correlating to these variables often reduces the simulation time by an appreciated amount.

The first few seconds of the simulations take a lot of time compared with the rest. There are two reasons for this. The first one is of course that the initial conditions are not perfect and do not match each other perfectly. The function for importing initial conditions in *Dymola* is unfortunately not working very well, especially not for as big models as in this master thesis. The other reason is that the backward differencing DASSL-code does not have any points before $t = 0$ and hence has less information about the solution.

Here are a list of some of the simplifications made during the project that had a big impact on the computational time and other problems:

- Steam system divided in half (symmetry), reduced the computational time a lot but some options for the modeling was lost.
- Small tanks removed from different places in the steam system, limited the problems with stiffness.
- Small tanks in preheaters, replaced with thermal adaptors, decreased computational time.
- One of the pumps and the surrounding components are removed in HEX3 .
- 5 instead of 10 regions in reactor and only one group of delayed neutrons instead of 6, reduced the computational time.
- Increased the tolerance from 0.0001 to 0.01, removed time consuming oscillations.
- Splitting the reactor pressure control into two parts, reduced the complexity.
- Only two feedwater pumps instead of three were used, to avoid leakage flow through the closed pump.

4.12 Whole model

A figure of the total model can be seen on the coverpage of this thesis. All main parts in the process system have been connected to each other. The only boundary condition that remains is the condenser. Note that only one of the two turbine branches is modeled, and the flow is instead scaled before and after the reactor.

Figures of the *Dymola*-models of the process systems in the steam and feed-water systems can be found in figure 4.6 and 4.7. Note the scaling components in the steam model that scale the flow to take the symmetry into consideration. The simple pressure losses in the feed water system have a very small nominal pressure drop and have a minor influence on the flow, the reason for their existence is to easier monitor the temperatures and pressures between the main components.

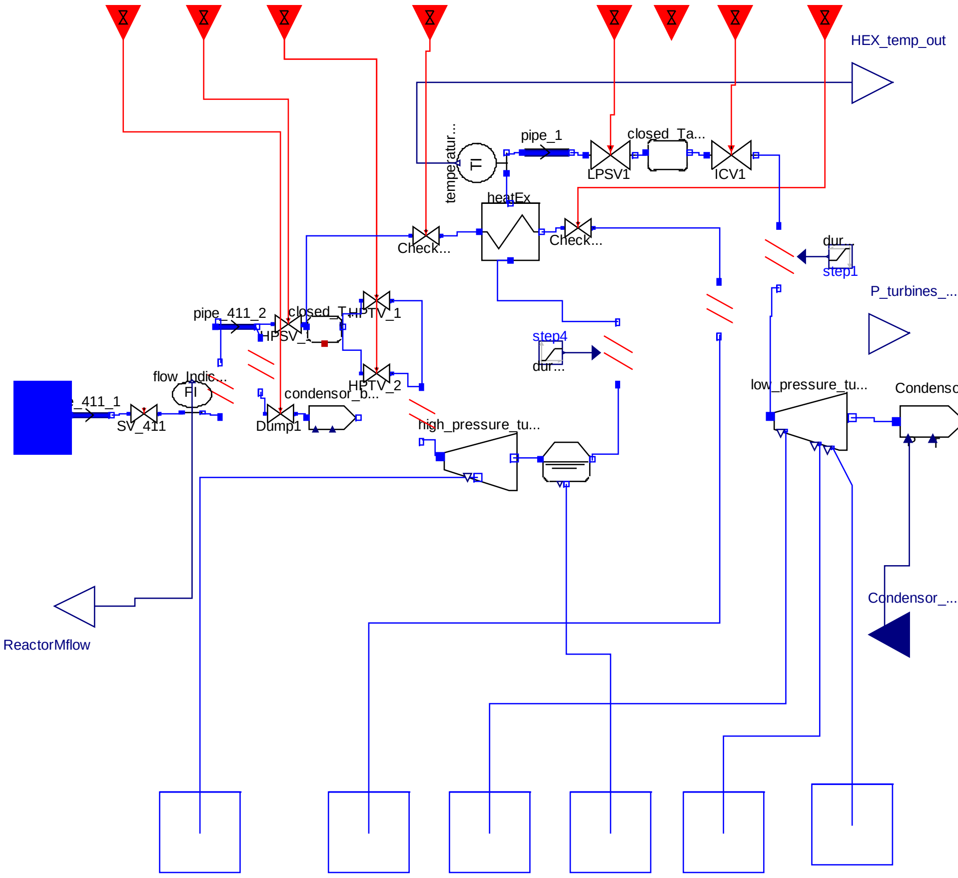


Figure 4.6: *Steam model. The hot steam from the reactor is coming from the left, connections from the control systems in the top, condensor boundary condition to the right and connections to the feedwater system in the bottom.*

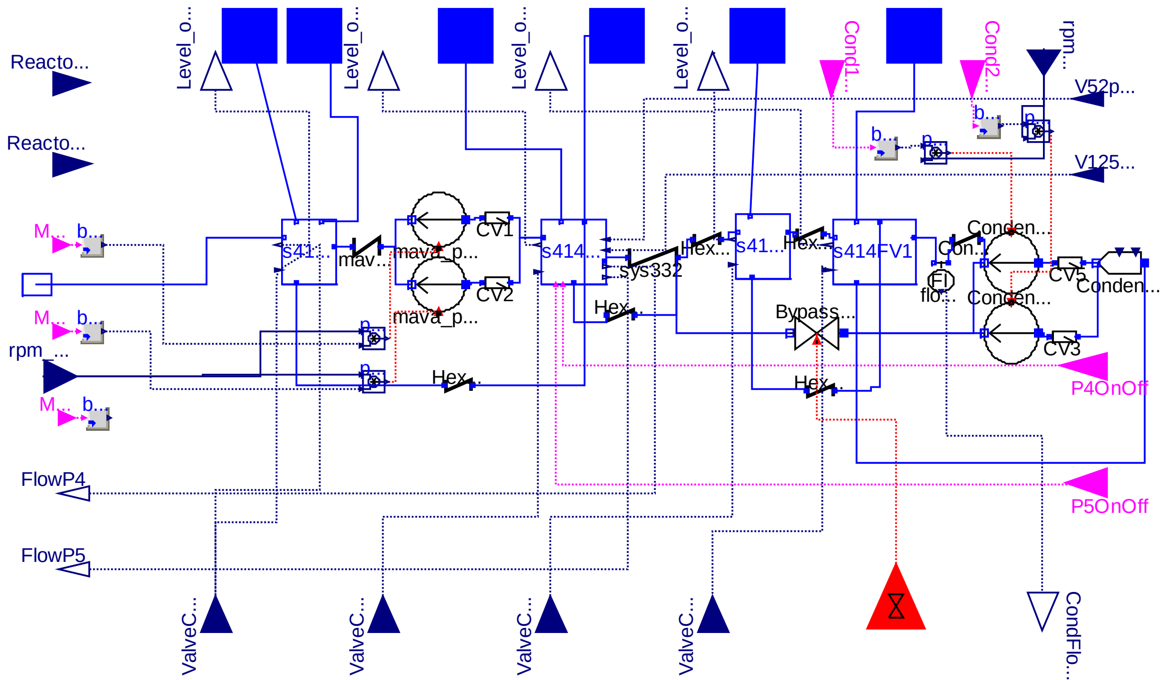


Figure 4.7: *Feedwater model. The flow from the condenser boundary condition comes from the right and travels through the pumps and heat exchangers. The ports for the flows from the steam system can be seen in the top, as well as the outputs for the heat exchanger levels. The control signals to the condensate valves in the preheaters are found in the bottom of the figure.*

CHAPTER 5

Results and discussion

This chapter contains results from three different cases to show what the model is capable of. During the project a lot of the work has been done in smaller parts of the model to calibrate and examine different parameters within a reasonable computational time. All the results in this section are however obtained from using the entire model with all the models and features mentioned in the modeling chapter. A star in the tables denotes an estimated value.

5.1 Full power and full load

The model has been calibrated against a full power case, see figure 2.1 combined with data from the continuously ongoing measurements at Ringhals. The reactor power is at 110% i.e 2500 MW and the generator load is 451 MW. The results for the pressure and temperatures in the steam system can be seen in figure 5.1, 5.2 and 5.3, 5.4 respectively. And the temperatures in the feedwater system can be seen in figure 5.5. Some of the values that the simulation are compared with are estimated due to lack of measurements.

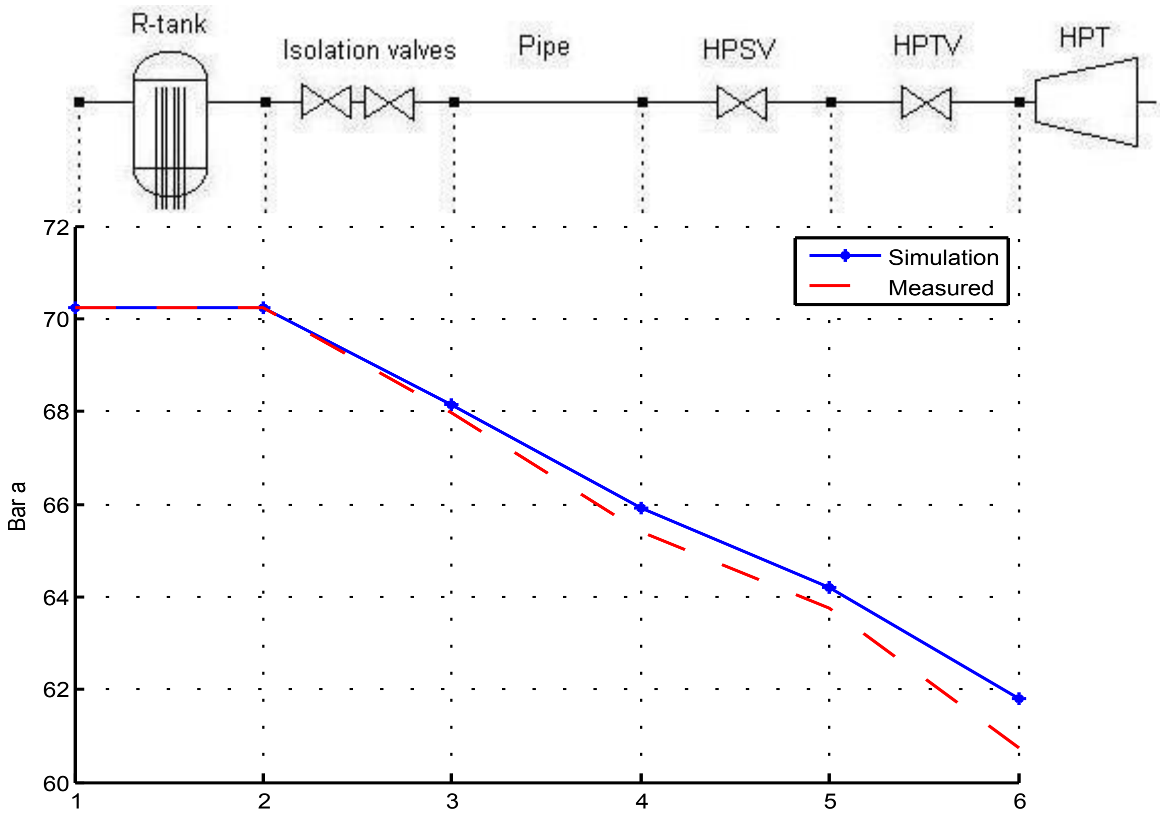


Figure 5.1: *Pressure drop from reactor to high pressure turbine at full power*

Table 5.1: Comparison between measured and simulated data of different positions in figure 5.1

Position	2	3	4	5	6
Measured	70,22	67,97	65,41	63,77	60,75
Simulated	70,22	68,16	65,90	64,20	61,80
Relative difference (%)	0,00	0,28	0,75	0,67	1,73

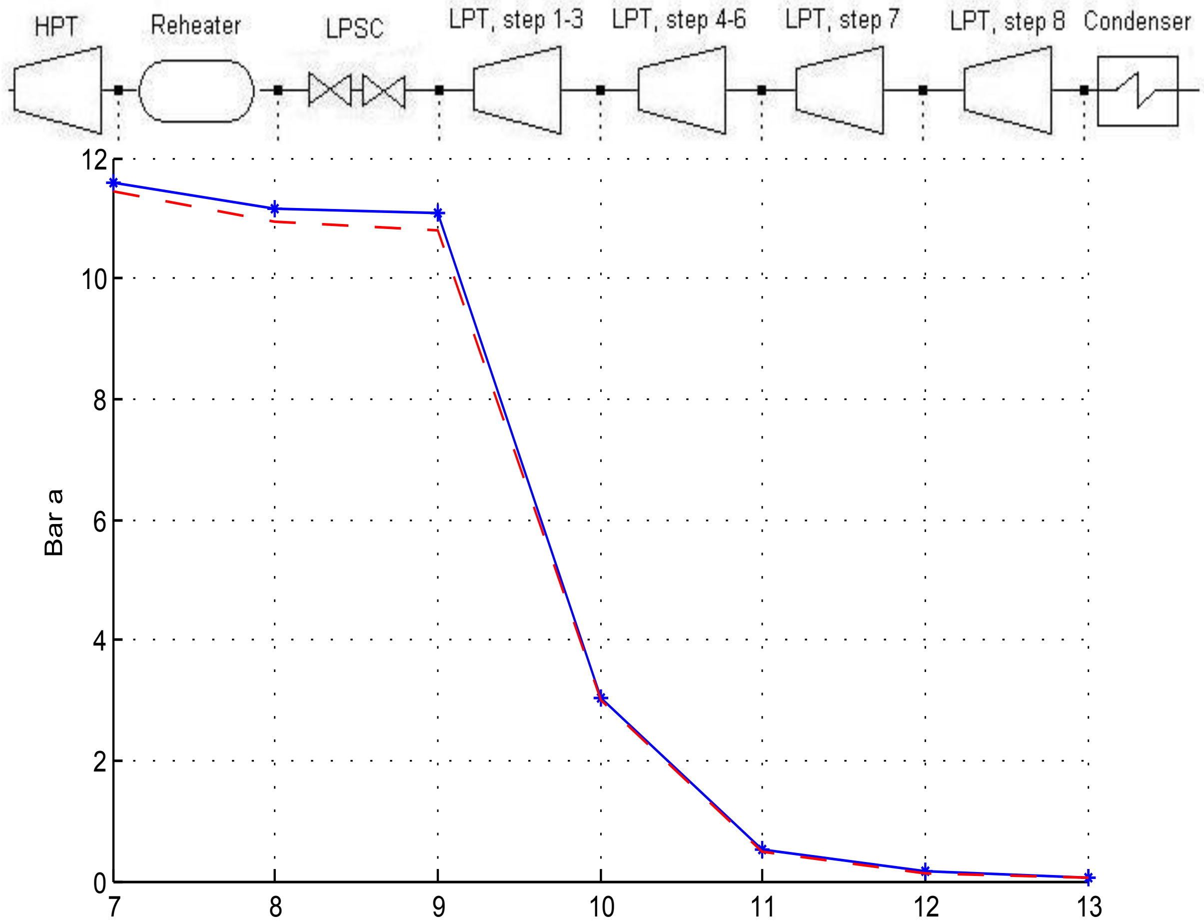


Figure 5.2: *Pressure drop from high pressure turbine to condensor at full power*

Table 5.2: Comparison between measured and simulated data in different positions of figure 5.2

Position	7	8	9	10	11	12	13
Measured	11,45*	10,94	10,80*	3,00	0,50	0,14	0,05
Simulated	11,58	11,16	11,09	3,04	0,51	0,15	0,05
Relative difference	1,14	2,01	2,69	1,47	1,88	2,32	0,00

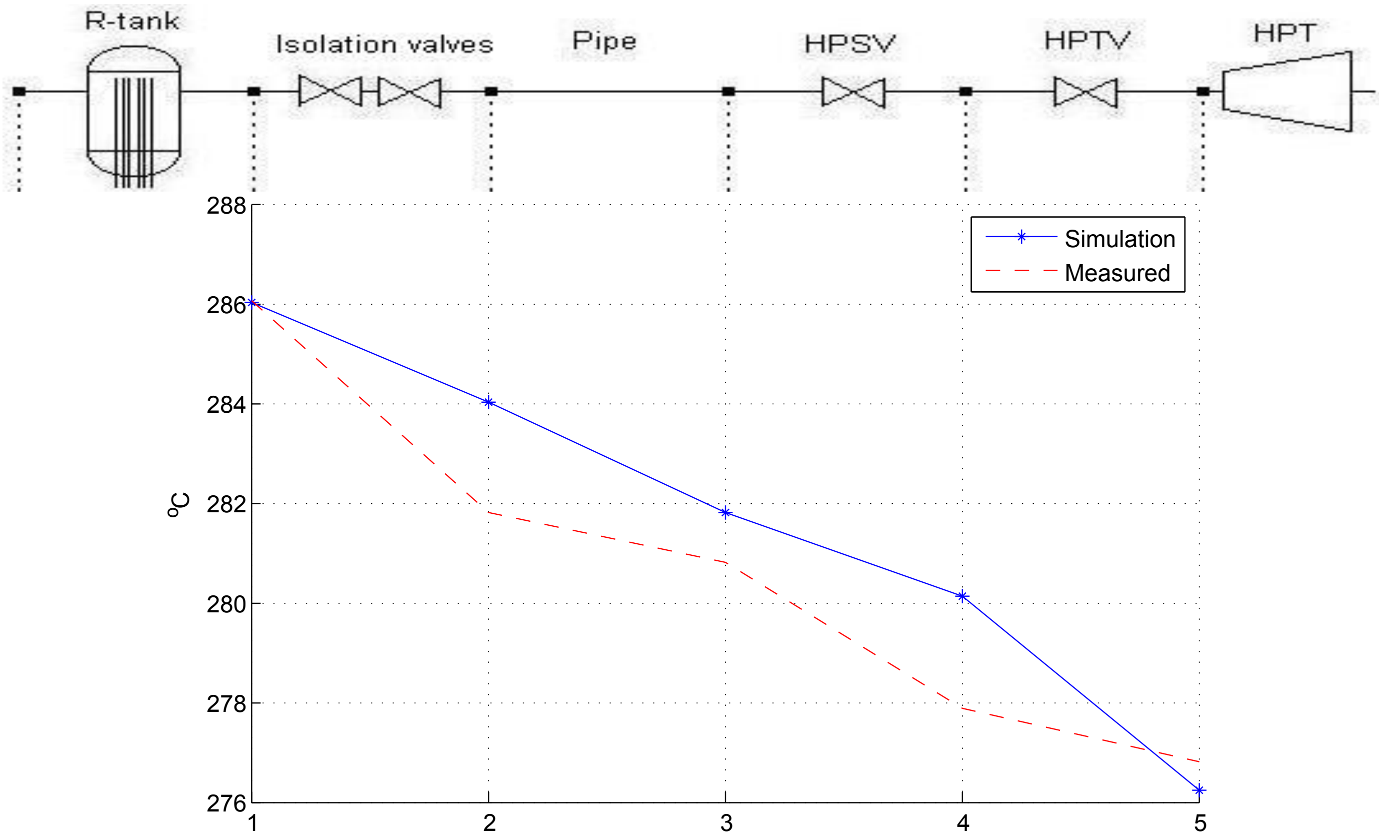


Figure 5.3: *Measured and simulated temperatures in the first part of the steam system at full power*

Table 5.3: Comparison between measured and simulated data in different positions of figure 5.3

Position	1	2	3	4	5
Measured	286,04	281,81	280,81	277,89	276,81*
Simulated	285,81	284,00	281,80	280,10	276,20
Relative difference (%)	-0,08	0,78	0,35	0,80	-0,22

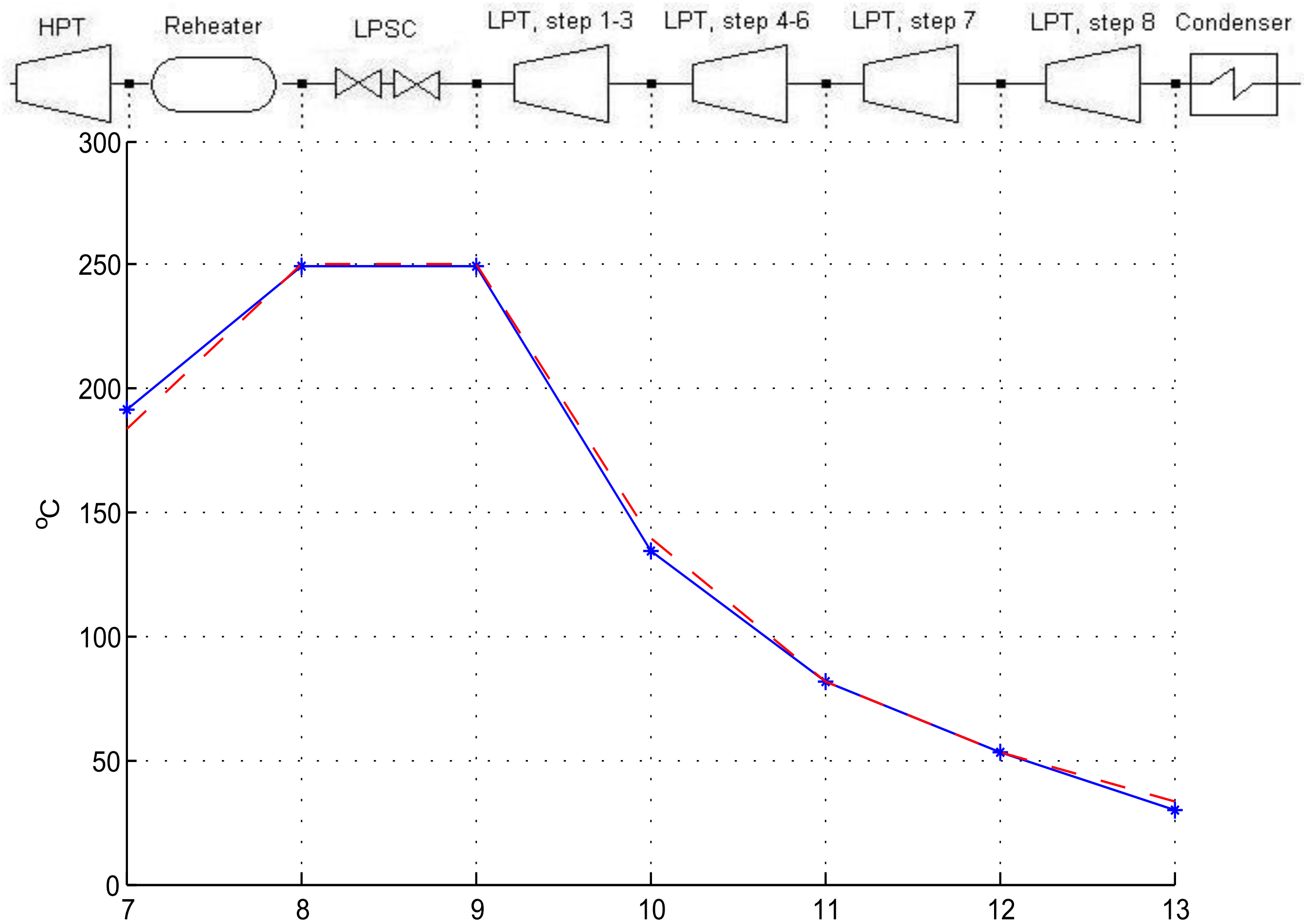


Figure 5.4: *Measured and simulated temperatures in the second part of the steam system at full power*

Table 5.4: Comparison between measured and simulated data of different positions in figure 5.4

Position	7	8	9	10	11	12	13
Measured	183,76	250,35	250,00	139,73	81,35*	52,78*	30,1
Simulated	191,20	249,30	249,20	134,50	81,39	52,98	29,80
Relative difference (%)	4,05	-0,42	-0,32	-3,74	0,05	0,38	-1,00

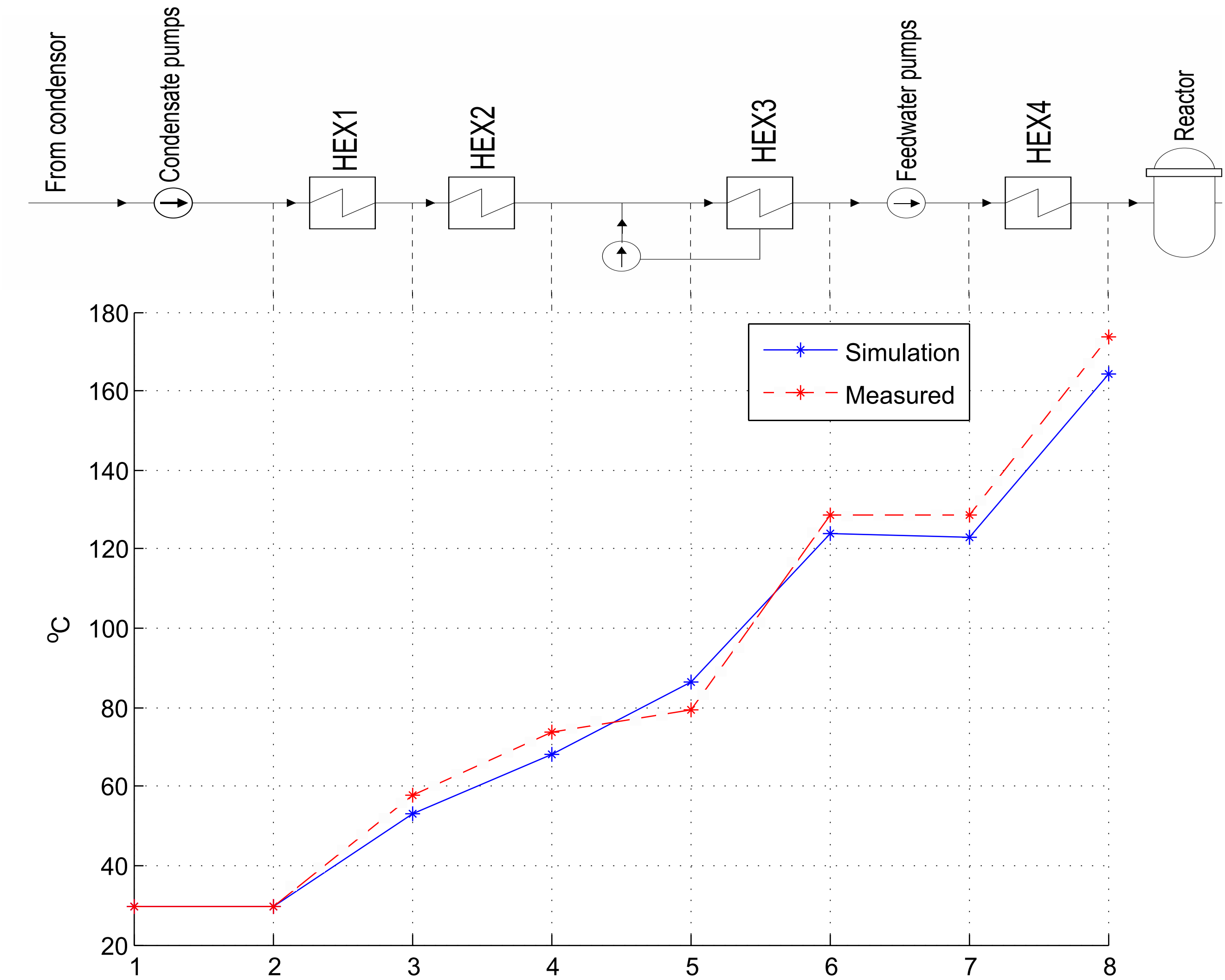


Figure 5.5: *Temperature rise in the feedwater system at full power*

Table 5.5: Comparison between measured and simulated data of different positions in figure 5.5

Position	1	2	3	4	5	6	7	8
Measured	29,80	29,80	57,90	73,50	79,40	128,70	128,70	173,80
Simulated	29,80	29,42	52,87	68,28	86,35	123,90	122,80	164,10
Relative difference (%)	0	-1,29	-8,69	-7,10	8,75	-3,73	-4,58	-5,58

The results from full power case are very good in most points, especially in the steam system. This is the case that the model has been calibrated against and the results could be improved if more time and effort were put into changing parameters in the system. But it is questionable how efficient and beneficial this would be without more accurate data and knowledge about the system.

Figure 5.1 and 5.2 show both the modeled and the measured pressure in the steam system at full power and full load, the relative difference is below 3% at all points. This very small difference has been seen as acceptable during this project because the time available for calibrating have been limited. The time available has instead been used for fixing bigger errors than these. The relative difference for the temperatures in figure 5.3 and 5.4 is also very small, only two points are almost reaching 4% whereas the rest are very good.

The results from the feedwater system are a bit more inaccurate, see figure 5.5. Especially the point before the heat exchanger 3. This preheater has been one of the main problems to get it working properly during the project. It is more complex than the others because it has 3 inflows to the shell-side, from HEX4, LPT and also one of the drainage tanks. Hence it has been hard to control the enthalpy of the condensate, but the flow rate is accurate.

The heating in the feed water flow is generally a bit too low compared with the measured points. Some effort was put into trying to increase the heating, but the control systems from the previous feed water model seems to counteract the changes. The differences are though at an acceptable level.

5.2 Reduced load

The data for this section are taken from the continuously ongoing measurements at *Ringhals 1* between 2008-05-03 00:00 and 2008-05-03 07:00. In this interval a transient happened consisting of three main things:

- Generator load drop from 442 MW to 312 MW.
- Reduced reactor power to 81 %.
- One of the low pressure stop valves was closed.

The closure of the valve that prevents the wet steam from the high pressure turbine from traveling to the lower reheater cannot be modeled directly in the model since the system is divided in half. Changes in the scaling components were instead made to simulate the closure and redirect all the steam to the upper reheater.

The results for the pressure and temperatures in the steam system can be seen in figure 5.6, 5.7 and 5.8, 5.9. The temperatures in the feedwater system can be seen in figure 5.10.

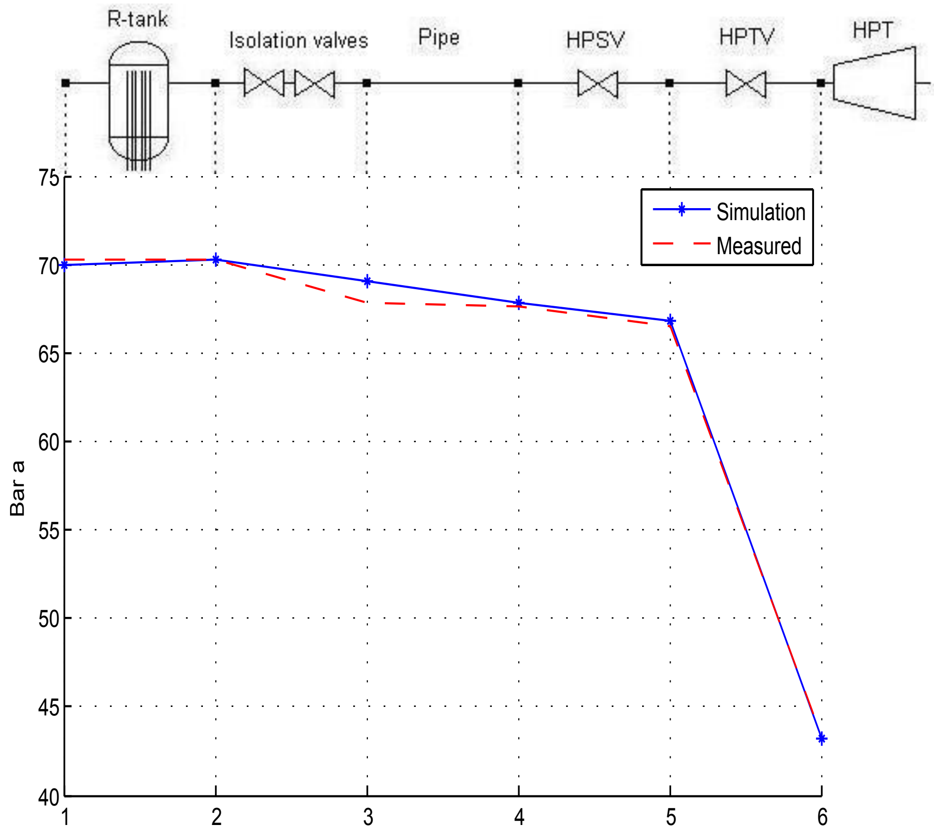


Figure 5.6: *Pressure drop from reactor to high pressure turbine at reduced power*

Table 5.6: Comparison between measured and simulated data of different positions in figure 5.6

Position	1	2	3	4	5
Measured	70,22	67,86	67,65	66,55	43,29
Simulated	70,22	69,02	67,82	66,83	42,18
Relative difference (%)	0,00	-1,68	-0,25	-0,42	2,63

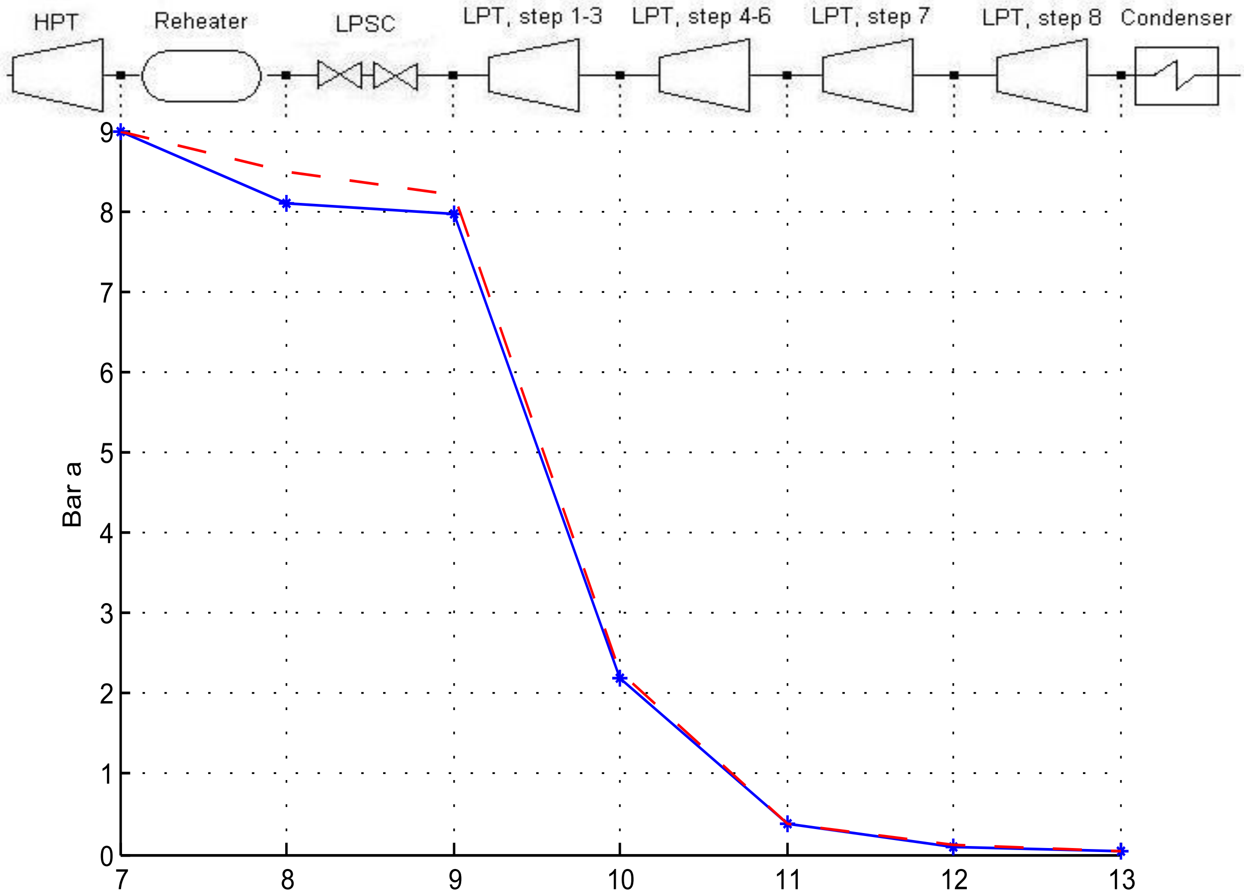


Figure 5.7: *Pressure drop from high pressure turbine to condenser at reduced power*

Table 5.7: Comparison between measured and simulated data of different positions in figure 5.7

Position	7	8	9	10	11	12	13
Measured	9,00*	8,48	8,20*	2,26	0,38	0,13	0,04
Simulated	8,98	8,09	7,96	2,20	0,37	0,10	0,04
Relative difference	0,20	4,87	3,03	2,82	2,98	24,16	1,32

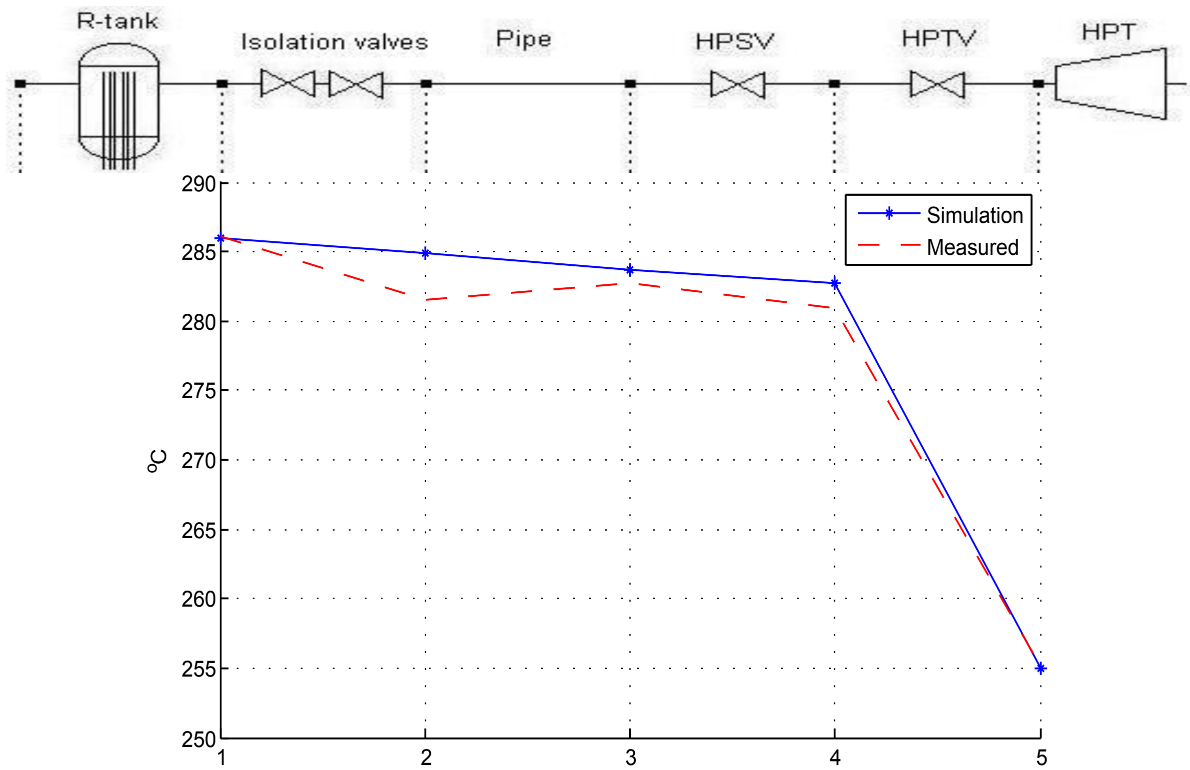


Figure 5.8: *Measured and simulated temperatures in the first part of the steam system at reduced power*

Table 5.8: Comparison between measured and simulated data of different positions in figure 5.8

Position	1	2	3	4	5
Measured	286,00	281,60	282,80	280,90	255,10
Simulated	286,00	284,90	283,70	282,70	254,90
Relative difference (%)	0,00	1,17	0,32	0,64	-0,08

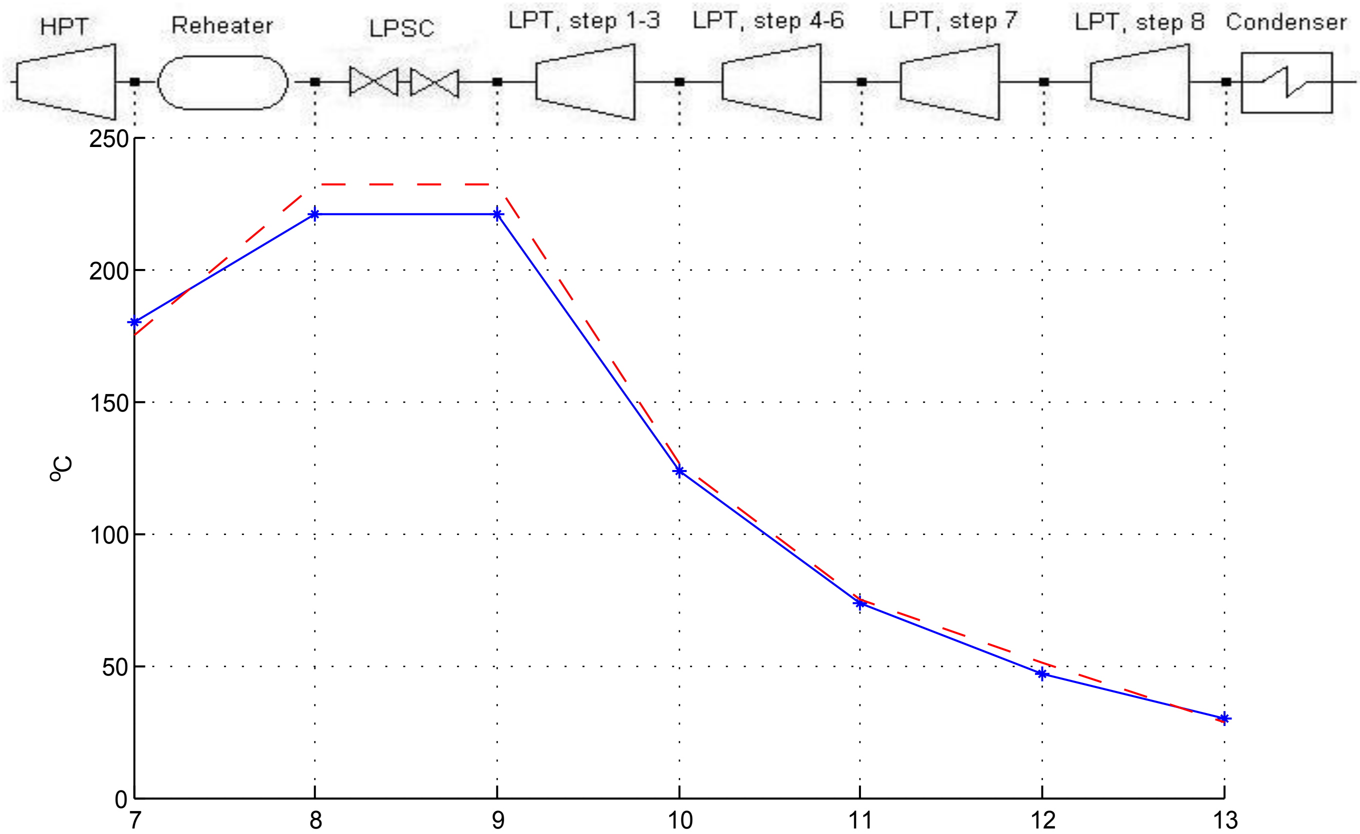


Figure 5.9: *Measured and simulated temperatures in the second part of the steam system at reduced power*

Table 5.9: Comparison between measured and simulated data of different positions in figure 5.9

Position	7	8	9	10	11	12	13
Measured	174,70	232,00	231,90*	126,20	74,76*	51,09*	28,32*
Simulated	179,80	221,10	220,80	123,30	73,93	46,71	28,32
Relative difference (%)	2,92	-4,70	-4,79	-2,30	-1,11	-8,57	0,00

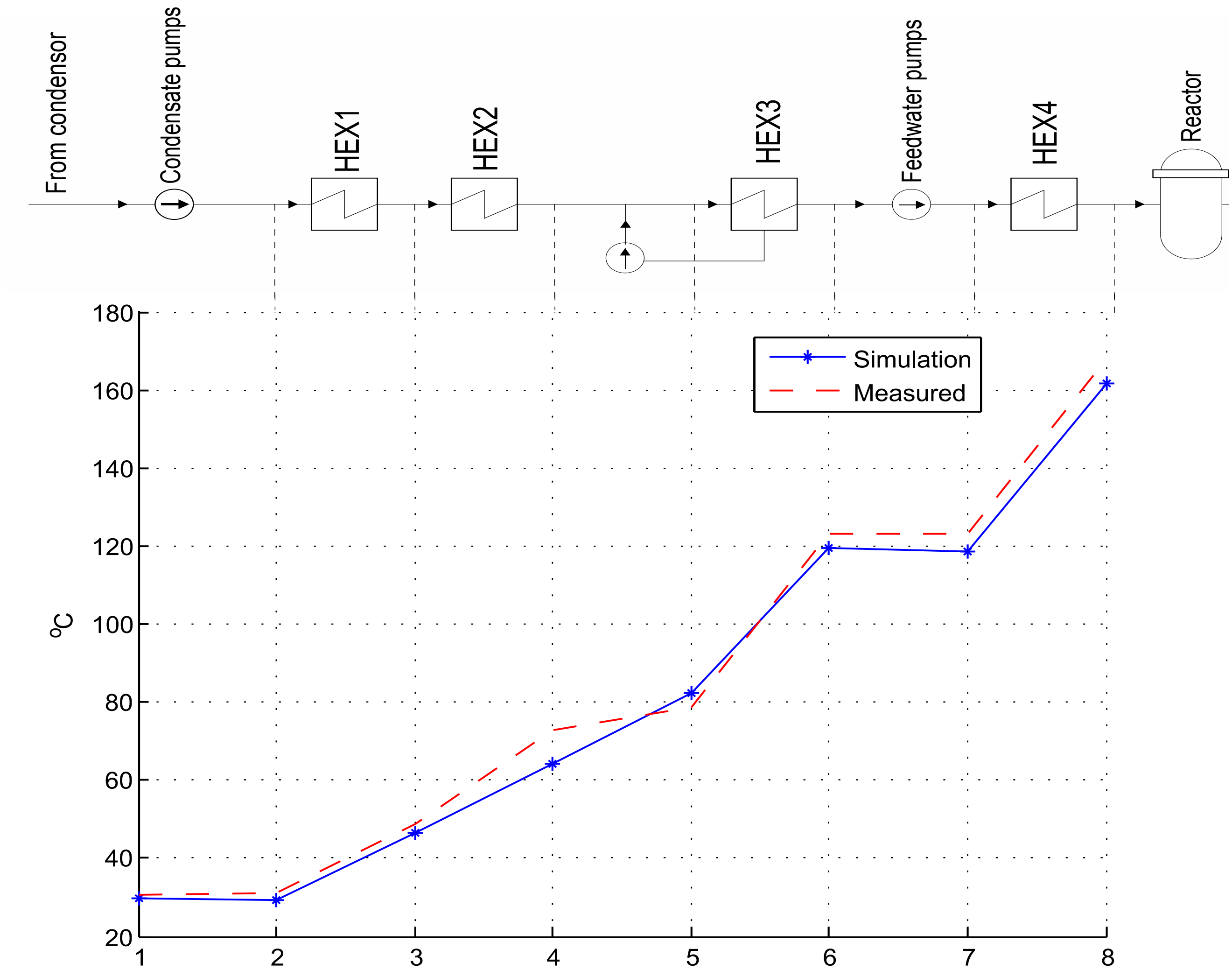


Figure 5.10: *Temperature rise in the feedwater system at reduced power*

Table 5.10: Comparison between measured and simulated data in different positions of figure 5.10

Position	1	2	3	4	5	6	7	8
Measured	30,50	31,10	48,60	72,70	78,60*	123,00	123,00*	168,10*
Simulated	29,82	29,37	46,67	64,02	82,46	119,50	118,50	161,40
Relative difference (%)	-2,23	-5,56	-3,97	-11,94	4,91	-2,85	-3,66	-3,99

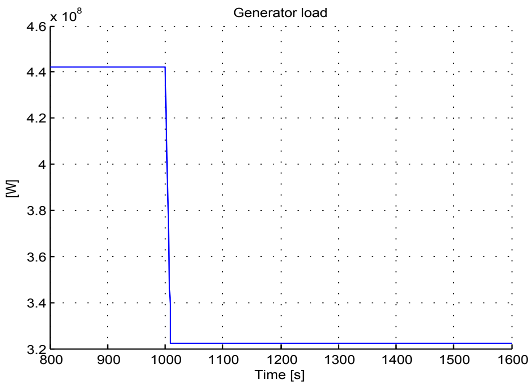
The results for the pressure in the steam system in figure 5.6 and 5.7 looks very good except for one point. The relative difference after the seventh step in the low pressure turbine is 24 %. This point was also troublesome in the previous model which only modeled the steam system, the explanation was that the efficiency of the seventh step was way too high [21]. The data for this measurement point are also very limited, there are even fewer values than for the other points. There might have been some problems with the equipment and the measurements for this point is probably less reliable.

As expected it is the same point which also contains the biggest error in temperature, see figure 5.8 and 5.9. Otherwise the simulation corresponds to the measured values and estimations very well. One can see that the reheater is unable to heat the steam to the setpoint of 250℃ because the flow on the shell side is doubled whereas the tubeside flow remains the same. The fact that the system and control systems manages to redirect all the flow to one of the reheaters with reasonable results is very promising for the model. The relative error for the temperature and pressure are below 5 % in all points in the vicinity of the reheater.. Note that the pressure drop over the HPTV is significantly larger than in the full power case since it has closed because of the reduced load on the turbines.

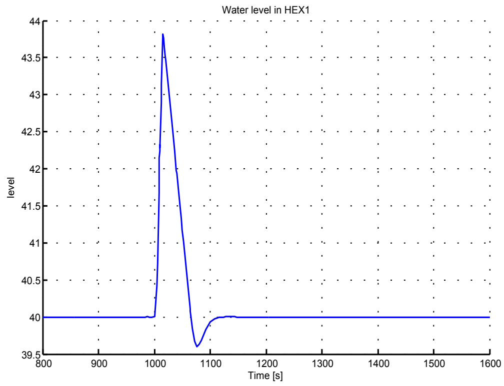
The temperatures in the feedwater system in this case is generally a bit lower than in the full power case, see figure 5.10. The relative differences are all below 9%, and the tendency is still that the heating is not sufficient to rise the temperature to the measured and estimated values. The influence of the lower temperature in the feedwater on the reactor is however not very large, the reason for this being that the feedwater is only a minor part of the main circulation flow.

5.3 Small transient

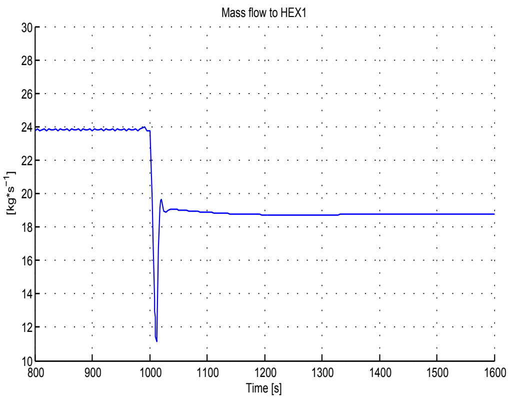
A small transient with a drop of generator load of 121 MW was made to show that this perturbation affects more or less the entire system. The effects in the different parts of the system at 6 different positions can be seen in 5.11. The transient was introduced at time 1000 s.



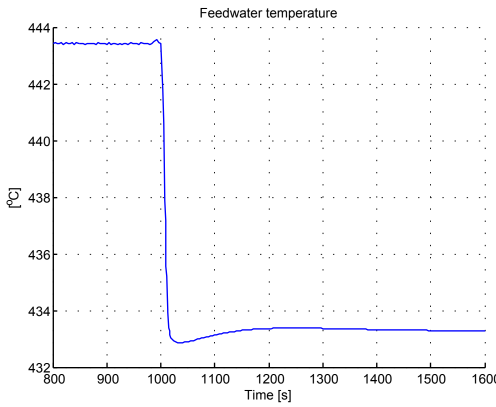
(a) *Generator load [W]*



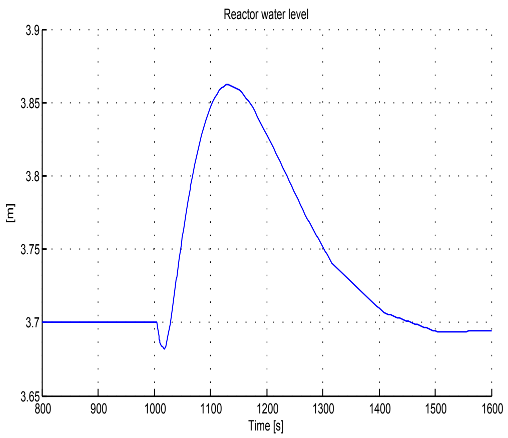
(b) *Waterlevel in first preheater [%]*



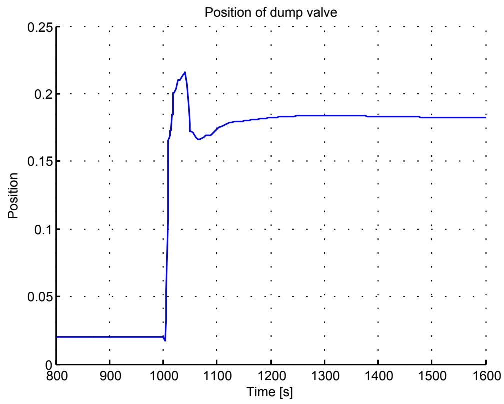
(c) *Flow from LPT to first pre-heater [kg/s]*



(d) *Feedwater temperature before the reactor [K]*



(e) *Water level in the reactor [m]*



(f) *Control signal to the dump valve*

Figure 5.11: *Data from different positions in the system during a small transient*

The drop in generator load of 121 MW results in that the frequency calculator block will calculate a frequency above 3000 rpm and thus the HPTVs will start to close. This closure will generate a pressure increase which immediately is taken care of by the dump valve, see figure 5.11f. Shutting the HPTVs also means a lower pressure after the valves which means a smaller flow to the pre-heaters, as can be seen in figure 5.11c. This lower flow of steam and pressure on the shellside of HEX1 means that the water level will increase before the control systems take it back to the desired level via the control valve for the condensate outflow. The temperature rise in the feedwater system is also reduced because of the lowered flowrate of hot steam, see figure 5.11b and 5.11d.

The water level in the reactor is also affected by the transient, as can be seen in figure 5.11e. Almost every variable in the system is affected somehow by the transient before it goes back to the same or another stable value. This experiment is nice for understanding what might happen during a smaller transient in the process loop of the plant, but it would be even better if it could be tested against a real case. It would probably not match the real case data very well in every point and more modifications and more advanced modeling would probably be needed.

One should also be aware that only one of the turbine branches is modeled, and the other one is assumed to be symmetric. The turbine branches are in reality not controlled independently of each other, so if this case should be compared too real data a generator load drop of 121 MW should be performed at the same time on both generators.

5.4 General discussion

Very much time of the work in this thesis has been spent trying to get *Dymola* running as expected. There have been many problems of various types, some of them were solved and other had to be avoided by finding another approach. The first issue is that there is not any good way for loading data for the initial state into *Dymola*. This means that lots of parameters manually have to be adjusted so that the simulation can start from a condition that is close to the required one. The first couple of seconds in the simulation will therefore always take big amounts of computational time because of the big transients before reaching a stable state.

Initiating transients were already an issue in the old smaller models, especially in the reactor where the reactor level took a long time to stabilize. These initiating transients are influencing and disturbing the other systems when the models are put together, resulting in even longer transients or even failure. This is another reason for the simple control system in the total model, the systems have to be able to handle the initiating transients in a neighboring system without failing.

It is very convenient that one does not have to convert the equations in *Dymola* to fit them into some kind of iterative scheme. The governing equations for each component are written in the component model, and then the component are connected to each other. One must though be careful so that the number of equations is equal to the number of unknowns. There are however some disadvantages with this procedure, the structure becomes less transparent and it can be very hard to find the source of a problem.

One of the main reasons that the simulation did not converge at times was that the state of the medium changed between the different regions in IF97, see figure 4.1. This could also be the case when initializing the problem if two nearby components had conditions that combined in the wrong way resulted in a point outside of these regions. There were also problems in components where there was a risk of the medium changing back and forth between one and two-phase flow. This phenomena did especially appear in the steambox above the reactor core after the steam separators and in the reheaters.

The strangest problems encountered have been when *Dymola* crashes when some kind of event happens. The event can be of various kinds for example a ramp for a transient that starts or stops or a valve that reaches its max opening. The only explanation for this is that the solver is forced to put a time-step where it is not beneficial for the solution algorithm, and convergence can hence not be found in the next step.

It was hard to find good data for the whole system when the plant is running at certain conditions, the more detailed measurements are often aimed at smaller specific parts of the system. More discussion and time is needed to talk to experts and collect more information about exactly what is happening in different parts of the process. Especially data about the flows and fluid states in between the turbines and the feedwater system. There is also a need for discussion about the uncertainty in the measurement data, which is unknown at the moment. It would be good to better trim the system and have more realistic models that responded better to changed circumstances in the vicinity.

A lot of effort was put into trying to model a large transient where the generator load dropped instantly to almost zero in one of the turbine branches. This would have been interesting because there are additional measurements from a similar case, where the reactor was running at 65 % power and one of the generators was generating 80 MW and the other one 405 MW. There were however a lot of problems when trying to implement this, some of them because of limitations and approximations in the model and some for *Dymola* to reach convergence and solve the equations. The first problem was that the simulation tends to fail when an event was introduced as mentioned above. One way of avoiding this was to introduce a small oscillation in the model, but not connected to the system. This measure limited the step size of the solver but made the simulation very time consuming and is not a possible solution in the long run.

The model itself is also not able to handle a transient of this magnitude. The control systems are not complex enough and some safety systems are missing, such as draining pipes from the tanks between the steam system and the feedwater system. Another thing that has to be considered is that the turbine branches are affecting each other, especially during a transient. If one wants to introduce a transient without simulating both turbine branches the effects have to be introduced in some other way, for example by scaling the flow appropriately. This was done during this project with good results, but the other limitations in the model made the timescales and results in the transient unrealistic.

Some attempts were also made to simulate both the turbine branches. The problem during the initialization did though become even larger. When *Dymola* is experiencing an issue with convergence it changes to a non-linear solver, and as the system of equations gets almost twice as large the solver cannot handle the issues at the initialization.

The component that probably limits the performance of the model the most is the Stodola turbine model. A turbine is in reality very complex and is of course hard to model. Especially the enthalpy of the steam exhaust was not as expected and had to be modified to get a correct mass flow through the preheaters.

Chapter 6

Conclusions

The main goal of this project was to have a working model for the entire process system at Ringhals 1, this goal has been reached with good results. The only boundary condition that remains is the condenser. The model was tested against two stationary cases where data were taken from different sources, among others from the continuous measurements at Ringhals 1. In the second test case one of the valves before the low pressure turbines was closed, and the model still managed to produce good results in most points.

To be able to develop and test the model, lots of simplifications and approximations had to be made to limit the computational time. These simplifications have of course affected the dynamics of the system. One can use the model to see how the system reacts to a transient but should be aware of the fact that the time scales and actual values might be different in the real case. One should also be aware of the fact that the models of the control systems are not very extensive, and their main purpose is to get the model running within a reasonable amount of time. Small transients can be tested with good results but large transients might require responses from the control systems that are not correctly modeled. There are still a lot of safety valves and other systems which can bypass the steam or liquid if anything has a malfunction, this is especially the case between the steam system and the feedwater system. These systems would be needed in order to introduce a bigger transient.

It is questionable whether *Dymola* is a good tool for modeling such a big system. The simulation are unfortunately sometimes crashing for unreasonable causes which requires some special adaptions to get around. But one should also be aware of the fact that there are a very big number of coupled equations which are solved within a reasonable time, so *Dymola* is definitely a powerful tool for modeling and is very straightforward because of the graphical approach.

Chapter 7

Future work

To increase the usefulness of the model one would have to start to make the model more complex. To be able to do that in a realistic way more data is needed, both measurement data of the state of the fluid in different parts of the system but also more knowledge about exactly how the system works in detail.

There are some parts of the model that require more attention than others. The turbines are modeled in a very simplified way which need to be improved if the system should respond realistically to changing circumstances. Another thing that would be very beneficial to the model is a real model for the generator. The third part that needs attention is probably the connections between the steam and feedwater system. More information about these pipes and drainage tanks are needed in order to make the model better. There is also a lot of possibilities to redirect steam and to dump steam to the condenser in this part of the system. To make the model able to handle a large transient, these safety valves and control systems need to be implemented.

It is possible to change solver in the newer versions of *Dymola*, if this feature was possible in version 6.1 the work might have been easier. DASSL can be used to get the model started and then *Dymola* can change to some kind of fixed iteration solver to be able to handle some of the issues later in the model when a transient is introduced.

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