# Electrical Modeling of a Thermal Power Station

Reinhard Kaisinger

KTH Electrical Engineering

Degree project in
Electric Power Systems
Second Level
Stockholm, Sweden 2011

XR-EE-ES 2011:010

# ELECTRICAL MODELING OF A THERMAL POWER STATION

Reinhard Kaisinger

Masters’ Degree Project
Kungliga Tekniska Högskolan (KTH)
Stockholm, Sweden 2011

XR-EE-ES 2011:010

# Table of Contents

# Appendices

**Number of Pages**

# Abstract

Physical systems are becoming more heterogeneous. Different engineering domains are interacting more and more. Therefore, it is desirable to have modeling tools that allow multi-domain modeling.

In thermal power plants, three engineering domains are of particular relevance: a) thermodynamics, b) mechanics and c) electrical engineering. The interaction of these three domains, among a few others, allows the generation of power, power control and power conversion.

The goals of this project are: a) to derive a model of a thermal power station and its responses to frequency deviations (primary control), and, b) to document how frequency control is carried out in Denmark and Germany.

A model of a thermal power plant has been derived in Dymola, a multi-domain modeling and simulation software tool. Fundamental components of thermal power plants, such as generator, steam turbine and turbine governor, are united in one overall model. Hence, the derived model integrates aspects of three engineering domains and captures respective phenomena relevant for frequency control. Recorded data from Block 1 of Amagerværket in Copenhagen, Denmark, is used to verify the model. Simulation results show that the model responds appropriately to frequency deviations and changes in power set point. Model simplifications are presented and motivated, and, for further model enhancements, possible future work is given.

Environmental concerns enhance the integration of renewable energy sources, such as wind and solar power, into electricity production. Wind and solar power can cause fluctuations in power generation which must be compensated by controllable generating units. Due to the large and steadily increasing share of renewable electricity generation in Denmark and Germany, frequency control is documented in these two countries. Frequency control follows different strategies in the ENTSO-E RG Continental Europe (former UCTE) and Nordic (former NORDEL) systems[1]. Load-frequency control is used in the ENTSO-E RG Continental Europe system as a centrally controlled frequency restoring action. In the future, the market for balancing reserves can be expected to be intensified.

---

[1] Since July 1st 2009, the UCTE, NORDEL and 4 other TSO associations in Europe are jointly represented by the ENTSO-E (European Network of Transmission System Operators for Electricity).

# Sammanfattning

Fysikaliska system blir alltmer förenade och olika naturvetenskapliga områden samverkar mer och mer. Därför är det önskvärt att ha ett modelleringsverktyg som kan hantera flera naturvetenskapliga domäner. Grundläggande naturvetenskapliga områden i termiska kraftverk är: a) termodynamik, b) mekanik och c) elektroteknik. Samverkan av dessa tre domäner, bland andra, möjliggör effektproduktion, effektreglering och effektomvandling.

Syftena med detta projekt är: a) att utveckla en modell av ett termiskt kraftverk vilken kan användas för att simulera primär frekvensreglering och b) att studera hur frekvensreglering hanteras i Danmark och Tyskland.

En modell av en termisk kraftverksanläggning har utvecklats i mjukvaran Dymola, vilken kan hantera flera naturvetenskapliga domäner. Kärnkomponenter i ett termiskt kraftverk, såsom generator, ångturbin och turbinregulator, sammanfattas i en övergripande modell. Det vill säga att modellen innehåller komponenter av tre olika naturvetenskapliga områden och viktiga fenomen, som är relevanta för frekvensreglering, vägs samman. Uppmätta data från block 1 vid Amagerværket i Köpenhamn, Danmark, används för att verifiera modellen. Det visas med simuleringsresultat att modellen reagerar lämpligt på frekvens- och lastreferensändringar. Förenklingar i modellen beskrivs och motiveras och möjligt arbete i framtiden föreslås.

Miljökrav och politiska styrmedel gör att andelen förnybara energikällor, som vind- och solkraft, i elproduktionen ökar. Både vind- och solkraft kan förorsaka effektfluktuationer vilka måste kompenseras med reglerbara kraftverksanläggningar. I Danmark och Tyskland är andelen förnybara energikällor i elproduktion relativt hög och den kommer att öka betydligt inom de närmaste åren. Därför dokumenteras frekvensreglering i dessa två länder. Frekvensreglering hanteras på olika sätt i ENTSO-E RG Kontinentaleuropa och ENTSO-E RG Norden system[2]. Det används Load-frequency control (LFC) i ENTSO-E RG Kontinentaleuropa vilket styrs centralt och har syftet att återställa frekvensen. Framtidens marknad för reglerreserver kommer troligen att intensifieras.

---

[2] Sedan 2009-07-01 är UCTE, NORDEL och 4 andra TSO organisationer i Europa förenade i ENTSO-E (European Network of Transmission System Operators for Electricity).

# Acknowledgement

The author wants to thank Vattenfall Research and Development AB for hosting this project. In particular, special thanks should be given to Jonas Persson and Jonas Funkquist for their encouragement, support and advice.

Furthermore, the author would like to thank Morten Sørensen, Steven Rovs Hansen, Jan Madvig, Lars Juul Konge and Hjalmar Hasselbalch of Vattenfall Denmark for their time and support.

Thanks to Mats Larsson and Fransisco Casella for their work on Modelica libraries which were used throughout this project.

The author wants to thank his wife Mary, parents Verena and Manfred and siblings Yvonne and Daniel for their love and endless support.

# Organization of the Report

This report is organized as follows.

In chapter 1, an introduction to this report is given.
In chapter 2, relevant theoretical background is described.
In chapter 3, modeling and simplifications therein are explained and documented.
In chapter 4, simulations and results are summarized and discussed.
In chapter 5, frequency control in Denmark and Germany is documented.
In chapter 6, conclusions are drawn and possible future work is suggested.
In chapter 7, a list of figures is provided, and in chapter 8 the bibliography is given.

# 1 Introduction

Physical systems are becoming more heterogeneous. Different engineering domains are interacting more and more. Therefore, it is desirable to have a modeling tool that allows multi-domain modeling [1].

Thermal power plants are conglomerats of a large number of facilities and control loops [2]. Their principal behaviour can be described with physical laws of three engineering domains: a) thermodynamics, b) mechanics and c) electrical engineering. When it comes to modeling of thermal power plants, the scope usually focuses on one of these domains whereas the others are considered very simplified or not at all.

One tool with multi-domain capability is Dymola. Dymola is based on the open, object-orientated modeling environment Modelica. The obejct-orientated approach permits hierachical modeling and flexible model re-usage. Acausality allows the usage of equations instead of assignments, i.e. the data flow direction does not need to be pre-defined [3]. Dymola comes with a number of libraries, each containing pre-made models originating from different engineering domains.

The electrical frequency in AC power systems is a fundamental quantity. In steady-state operation, the generated power equals the consumed power plus the losses. As long this balance holds, the electrical frequency remains constant. When, however, this balance is not maintained, the frequency starts to increase or decrease. Since large frequency deviations cannot be tolerated, these deviations must be counteracted and the system frequency stabilized.

Frequency stabilizing action is achieved via power plants participating in frequency control. These plants adjust their production as a response to variations in the electrical frequency. The turbine governor responds to freqeuncy variations by changing turbine control valve positions and, therewith, regulates the generated power. Eventually, the frequency settles again and remains constant, i.e. a new steady-state point is obtained.

In Denmark, thermal power plants are in operation that do not cover base load. In contrary, these plants run only for the sake of frequency control. The configuration of these plants was modified so that fast responses in power generation are possible. This effect is usually achieved by lowering the overall plant efficiency. However, the higher price paid for balancing reserves, relative to the electricity price, makes it possible to run these plants profitably [4].

The goals of this project are: a) to derive a model of a thermal power station and its responses to frequency deviations (primary control) (see chapters 3 and 4) and b) to document how frequency control is carried out in Denmark and Germany (see chapter 5).

The scope of the model of the thermal power station is to capture phenomena, in both the electrical and the thermo-dynamical domain, relevant for primary frequency control. Emphasizing its multi-domain capability, Dymola is found to be a good candidate for being used for this task. Two additional model libraries, `ObjectStab` and `ThermoPower`, were used in order to accomplish the modeling task. Plant data from block 1 of Amagerværket located in Copenhagen, Denmark, was used. Simulation results were run against measurements from Amagerværket in order to validate the model.

The progressive penetration of renewable energy sources into Denmark's and Germany's electricity production makes frequency control in both countries a challenging task. Wind power in Denmark and wind- and solar power in Germany cause fluctuations in electricity generation which need to be taken care of. Until now, both countries could rely on their respective neighboring countries to support them with sufficient balancing power. In future, however, these countries may require their own balancing reserves after having integrated large capacities of renewable energy sources in their respective power systems. In addition, with ambitious plans towards a low emission and nuclear free electricity generation, Denmark and Germany enhance the installation of even more renewable energy sources [5], [6].

This project was initiated by and it was carried out at Vattenfall Research and Development AB in Råcksta, Stockholm.

# 2 Background

In this chapter, fundamental facilities in thermal power plants and their purposes are described. Additionally, operation and control of thermal power plants is documented, and information regarding frequency control is presented.

## 2.1 Facilities in a Thermal Power Plant

Thermal power plants consist of a large number of facilities. One major component is the boiler together with the furnace where the combustion of the fuel takes place and steam is generated. The thermodynamic cycle contains a number of heaters, pumps and valves, all serving the purpose of operating and controlling the plant. The steam turbine (or prime mover) converts the energy stored in steam into mechanical torque. Via the common shaft, the generator (or alternator) converts mechanical kinetic energy into electric energy. The generator is connected to the domestic grid via a step-up transformer and protected by an electrical protection system. An excitation system controls the generator’s output voltage by adjusting the reactive power generation. The turbine governor, a controlling link between generator and turbine, regulates the active power fed into the power system.

Figure 2-1 together with table 2-1 show the major components in a fossil-fueled thermal power station without district heating supply.

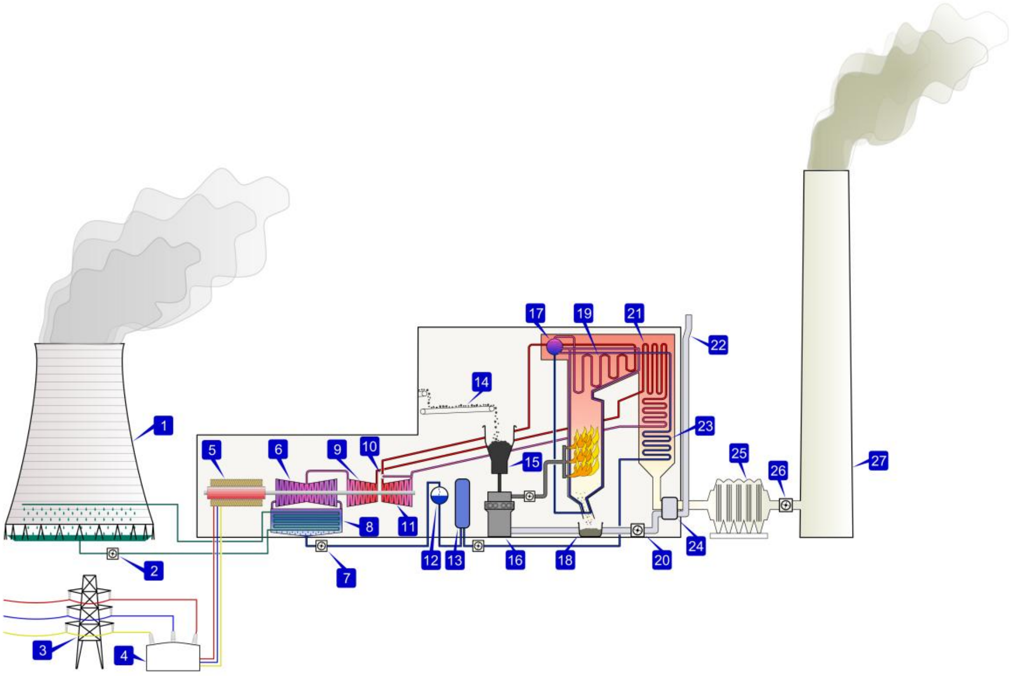

**Figure 2-1: Main components in a thermal, fossil-fueled power plant [7]**

**Table 2-1: Key to figure 2-1 [7]**

| | | | | | |
|---|---|---|---|---|---|
| **1** | Cooling tower | **10** | Steam governor valve | **19** | Super heater |
| **2** | Cooling water pump | **11** | High pressure turbine | **20** | Forced draught fan |
| **3** | Transmission line | **12** | Deaerator | **21** | Re-heater |
| **4** | Step-up transformer | **13** | Feed water heater | **22** | Air intake |
| **5** | Electric generator | **14** | Coal conveyor | **23** | Economizer |
| **6** | Low pressure turbine | **15** | Coal hopper | **24** | Air pre-heater |
| **7** | Condensate extraction pump | **16** | Coal pulverizer | **25** | Precipitator |
| **8** | Condenser | **17** | Boiler drum | **26** | Induced draught fan |
| **9** | Intermediate pressure turbine | **18** | Ash hopper | **27** | Chimney Stack |

## 2.2 Thermal Power Plant Operation

The overall operation of a thermal power plant is rather complex and involves many tasks, most of which are precisely controlled and coordinated by a central master control instance [2].

Below, major processes in thermal power plants and their control are described. The focus lies on fossil-fueled thermal power plants, and solar- or geo-thermal power plants are not described.

### 2.2.1 Fuel and Combustion

The fuel is moved via conveyer belts or pumps from its storage to the boiler. Along the way from storage to furnace, solid fuels are grinded or chopped so that it is easier to mix them with air [2]. In biomass power plants, several kinds of fuel, such as straw and pellets, may be mixed in order to improve the combustion process [8].

Both the fuel and air are blown into the burner where the combustion takes place. The fuel to air ratio determines the energy output of the boiler and the toxicity of the exhaust gases, i.e. the completeness of the combustion. Incomplete combustion with too little air leads to black smoke, poisonous carbon monoxide and danger of unburned fuel remaining in the boiler, whereas air excess causes unwanted $NO_x$ and $SO_x$ emissions and reduced boiler efficiency. Different fuels, and even different qualities of one kind of fuel, require a well adjusted combustion process [2].

The generated heat is finally absorbed by the feed water via convection and radiation mechanisms [2].

### 2.2.2 Rankine Cycle

Today, most thermal power plants follow the thermodynamic Rankine cycle, a practical implementation of the Carnot cycle which achieves efficiencies between 30 and 47 % [2]. Figure 2-2 shows a simplified steam cycle in a thermal power plant, and, figure 2-3 shows the corresponding temperature-entropy (T-s) diagram. The most important processes in the Rankine cycle are listed in table 2-2.

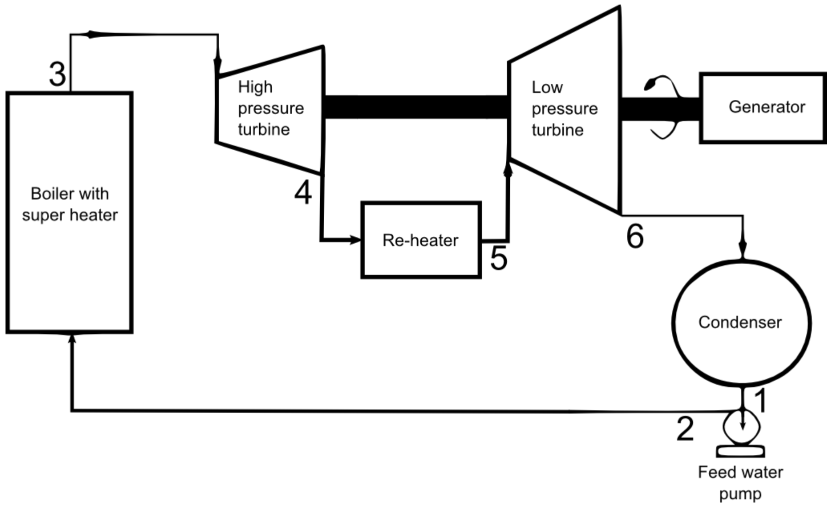

Figure 2-2: Steam cycle with two turbine stages, re-heater and one feed-water pump

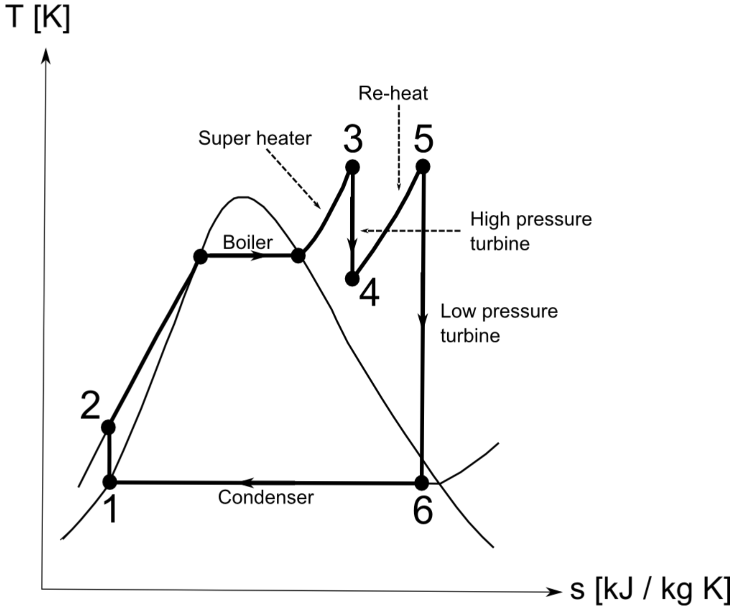

Figure 2-3: T-s diagram of a Rankine Cycle with super heating and single re-heat corresponding to figure 2-2

Table 2-2: Major processes in the steam cycle shown in figure 2-2 and figure 2-3

| **Process** | **Description** |
|---|---|
| **1 → 2** | Pumping feed water from condenser to pre-heaters and boiler |
| **2 → 3** | Heating and super heating in the boiler |
| **3 → 4** | Steam expansion in high pressure turbine |
| **4 → 5** | Re-heating |
| **5 → 6** | Steam expansion in low pressure turbine |
| **6 → 1** | Cooling in the condenser |

The steam cycle is conventionally analyzed beginning with the feed-water flow from the condenser. The condenser holds a large water reservoir at relatively low temperature and low pressure. Feed water coming from the condenser is pumped through a number of pre-heaters (not shown in figure 2-2 but see figure 2-4 instead). These pre-heaters draw their heat from steam which is bled from turbines or bypassed turbines. Turbine bleding is the extraction of steam from different turbine stages and allows increasing overall efficiency of the steam cycle.

Going through pre-heaters, temperature and pressure of the media are rising. The economizer is the last stage of pre-heating located in the flue gas channel before the media enters the evaporator, where the water is heated to its saturation point. The saturated steam then enters the drum, where the resulting steam is separated from incoming water. Once-through boilers are not equipped with a drum, and, thus, the steam is directly supplied to the turbine.

In the turbine, the kinetic energy of the dry, saturated vapor is converted into mechanical torque through axial steam expansion. A turbine usually consists of several stages such as high, intermediate and low pressure sections. Between these sections, the steam exiting the previous turbine stage may be returned to the boiler and re-heated before it is supplied into the next turbine stage. This re-heating increases the overall efficiency of the steam cycle.

Exiting the last turbine section, the now expanded steam is either used to supply a district heating system and/or is condensed back into liquid by cooling water. Some thermal power plants with heat supply for district heating do not have any additional cooling facility. These kinds of power plants cannot generate electricity when no heat is demanded, since the media cannot be cooled [4].

## 2.3 Thermal Power Plant Control

Modern power plants are complex arrangements of pipes and machines with a high number of interacting control loops, support- and safety-systems. All components involved in controlling, receive their set points directly or indirectly from the top of the control hierarchy, the unit master controller [2].

Valves are fast means of controlling power generation and ensure safe operation in thermal power plants. Three main valves in a typical steam cycle are briefly described below.

- Turbine valves are used to control the inlet pressure levels at different turbine sections, i.e. high pressure, intermediate pressure and low pressure section.
- Bypass valves are used to bypass steam so that it is not utilized in the turbine but for other purposes such as pre-heating or district heating.
- Safety valves are used in case of overpressure or at other irregular occasions. Their purpose serves the safe operation and prevention of damage.

Thermal power plants can be operated in different control modes. A short, by all means not complete, list of possible control modes is given below [9], [10], [11]:

- **Boiler following mode:** The governor controls the turbine valves being able to respond quickly to changes in power output demand. The firing is controlled by the master pressure controller. This mode of operation is not the most efficient option since governor valve throttling reduces the steam flow and causes energy losses.

- **Turbine following mode:** In this mode of operation, the output power of the turbine is primarily determined by the steam output of the boiler and not by turbine valves. The firing is set according to the desired load. Valves positions are set in order to keep the pressure at the turbine at a constant level. Turbine following mode is used in base load units and does not allow fast changes in power output, as required for frequency controlling action.
- **Sliding pressure mode:** Instead of throttling, the steam valves are completely open. Thus, the unit efficiency is increasing, especially at low load points. For the sake of safety, fast responding safety valves are necessary when running in this mode.
- **Turbine island operation:** When the generator is disconnected from the power system, the power plant must be able to maintain steady-state operation. In this case, firing in the boiler must be controlled as well as both turbine and bypass valves provide the power plant’s own consumption. A quantity of a high importance is shaft speed which must be kept close to its nominal value. Not all thermal power plants may be able to sustain island operation mode.

Different controllers and control loops serve different purposes, but are, nonetheless, connected and operate as one, overall system.

### 2.3.1 Turbine Governor

The definition of the term ‘turbine governor’ or simply ‘governor’ is vague and used differently in literature. Most commonly, however, a governor controls the turbine valves in order to achieve desired output power from the generator. Furthermore, a governor may control bypass valves and may respond to electrical frequency deviations by controlling the turbine valves, see section 2.5.

The turbine governor is by far the most important controller in this project. It allows turbine valve control which is essential when it comes to primary frequency control. Other governing systems, such as bypass or boiler governor, are not discussed here.

## 2.4 Amagerværket Block 1

Plant data from block 1 of Amagerværket located in Copenhagen, Denmark, was used to verify the model. This block is currently undergoing a commissioning phase.

Block 1 in Amagerværket has a rated gross electrical power output of 80 MW and additional heat supply of 250 MJ/s [12]. The block supplies steam to a district heating system, and the block does not have any other cooling facilities. Due to the absence of cooling facilities, such as a cooling tower, the unit cannot produce electricity when the demand for heat is low, e.g. during warm summer days.

The power plant can be fired by several fuels: oil, coal and biomass [12]. When fired with biomass, chopped straw and wood pellets are mixed in order to avoid the accumulation of slag in the boiler [8].

The nominal steam temperature is 562 ˚C, and the nominal pressure is 185 bar [12]. These values may, however, deviate between different fuels.

The steam turbine consists of a high pressure (HP) section and an intermediate pressure section (IP) compounded in a tandem configuration. A large part of the steam leaving the high pressure turbine section is re-heated before it is fed into the intermediate pressure turbine. The intermediate pressure turbine has one major steam extraction. The steam exiting the intermediate pressure turbine section is supplied to the district heating system. Both turbine sections are equipped with control valves (CV).

Bypass valves allow bypassing steam both the high pressure turbine (HPT) section and the intermediate turbine (IPT) section. Steam bypassed the high pressure turbine section is supplied back into boiler. Steam bypassed the intermediate pressure turbine stage is supplied to the district heating system. Figure 2-4 illustrates essential components of the steam cycle at Amagerværket Block 1.

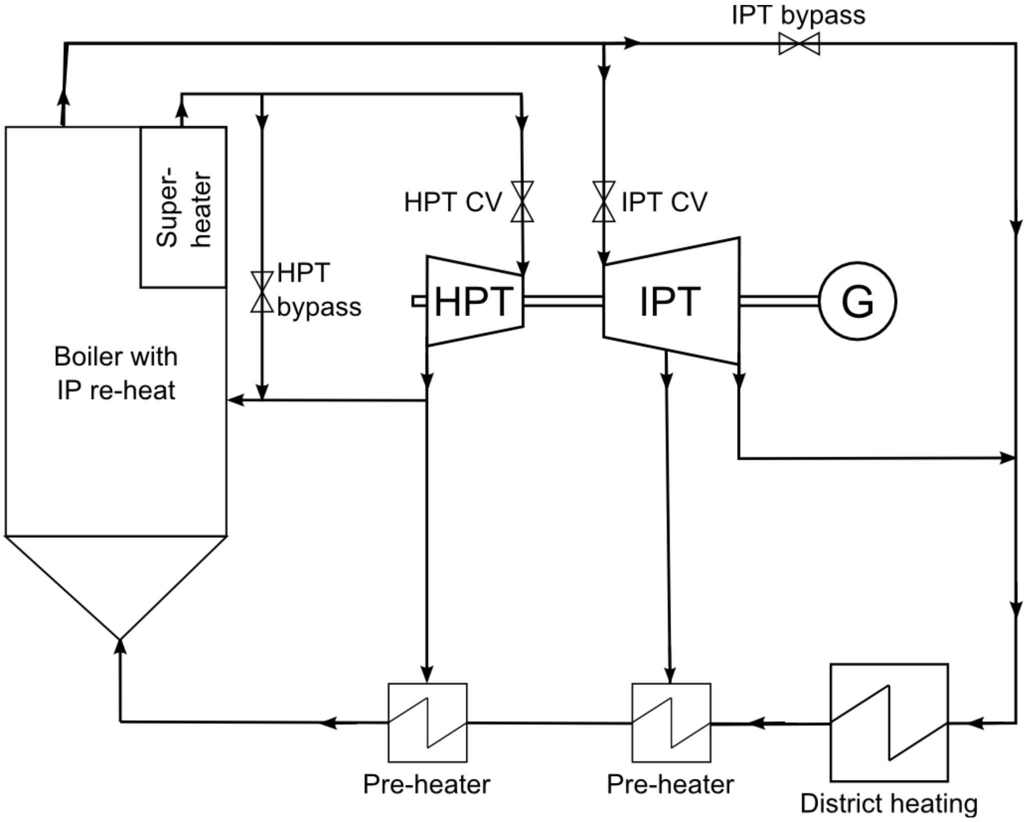

**Figure 2-4: Simplified steam cycle at Amagerværket Block 1**

The generator and the steam turbine are mounted on a common shaft.

The firing in the boiler and the positioning of valves are fundamental tasks of the overall control system of any power plant, see section 2.3. At Amagerværket Block 1, a possible distinction between different controllers is given by: boiler governor, turbine governor and bypass governor. This distinction is used in table 2-3 which illustrates different tasks during various modes of operation at Amagerværket Block 1.

**Table 2-3: Different modes of operation at Amagerværket Block 1**

| **Mode of Operation** | **Boiler Governor** | **Turbine Governor** | **Bypass Governor** |
|---|---|---|---|
| **Turbine out of Operation** | Steam into district heating | - | Boiler pressure |
| **Turbine Island Operation** | Steam into district heating | Speed of turbine shaft | Boiler pressure |
| **Natural floating production – Turbine Follow** | Steam into district heating | Boiler pressure | Safety |
| **Natural floating production – Boiler Follow** | Boiler pressure | Steam into district heating | Safety |
| **Reduced Production** | Steam into district heating | Electrical output power | Boiler pressure |

## 2.5 Frequency Control

In steady-state operation, the power generation equals the power consumption including losses [9]. Consequently, the system frequency does not deviate but remains constant.

When there is an imbalance between generated and consumed power, the system frequency does not remain constant any longer. If electricity production is higher than consumption, the system frequency is increasing. Conversely, the system frequency is decreasing when consumption is higher than production. Such unbalanced operation may occur after a sudden loss of a generation capacity or consuming load, see section 4.3 where a sudden generation capacity loss in the ENTSO-E RG Nordic power system is simulated. In order to keep the frequency close to its nominal values, frequency control is implemented in power systems.

Frequency control is carried out differently in different power systems. The focus of this report lies on frequency control in both the ENTSO-E RG Continental Europe and ENTSO-E RG Nordic power systems.

### 2.5.1 Frequency Control in the ENTSO-E RG Continental Europe Power System

In the ENTSO-E RG Continental Europe power system, three different frequency control actions are commonly referred to: a) primary frequency control, b) secondary frequency control and c) tertiary frequency control. These three frequency control actions are hierarchically activated, beginning with primary frequency control, followed by secondary frequency control, and finally tertiary frequency control. Figure 2-5 shows the hierarchical activation of balancing reserves in the ENTSO-E RG Continental Europe power system.

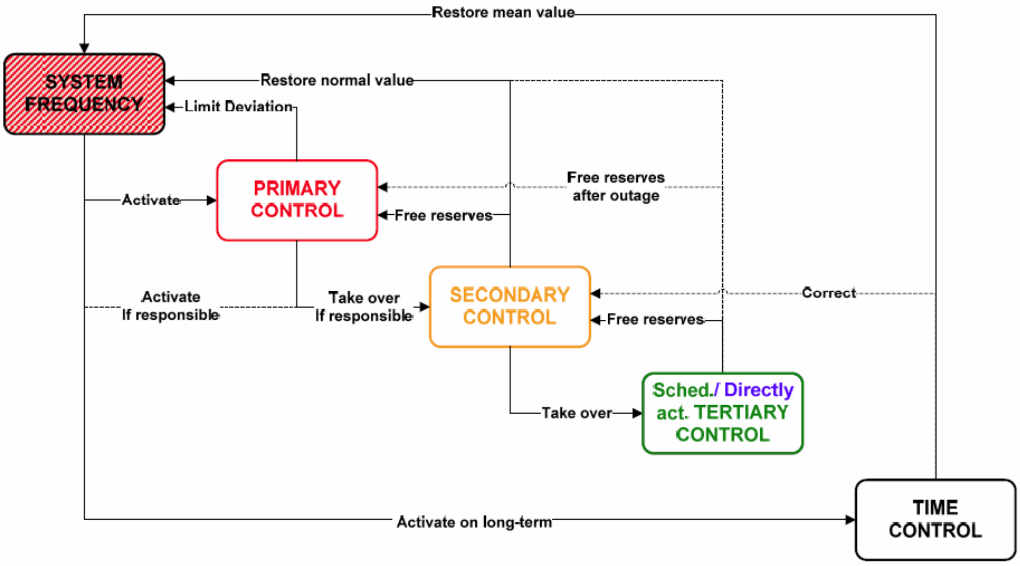

**Figure 2-5: Schematic representation of frequency control in the ENTSO-E RG Continental Europe system power (taken from [13])**

Figure 2-6 shows the time frames of the three frequency control actions in the ENTSO-E RG Continental Europe power system. The orange, dotted line shows a frequency deviation.

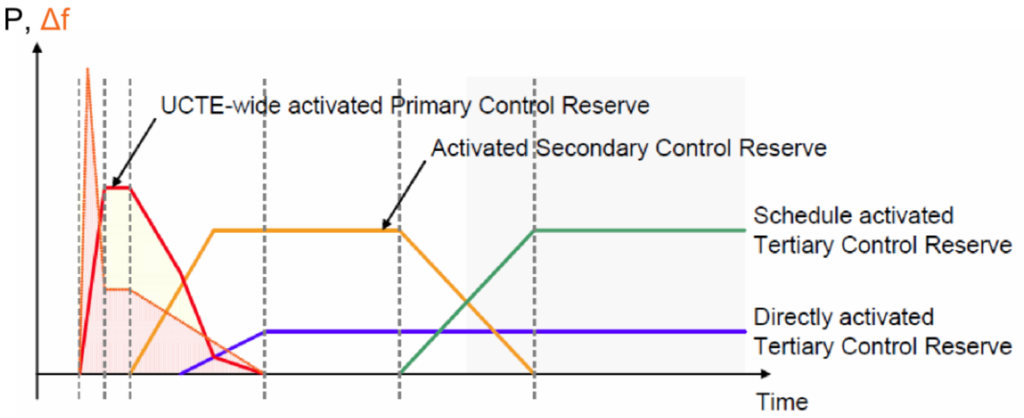

**Figure 2-6: Time frame frequency control action in the ENTSO-E RG Continental Europe power system (taken from [13])**

### 2.5.2 Frequency Control in the ENTSO-E RG Nordic Power System

In the ENTSO-E RG Nordic power system, different strategies for frequency control are used. A distinction between different balancing reserves is given by: a) frequency-controlled normal reserves (FNR), b) frequency-controlled disturbance reserves (FDR), and, c) manual reserves. Figure 2-7 illustrates under which conditions FNR and FDR are activated.

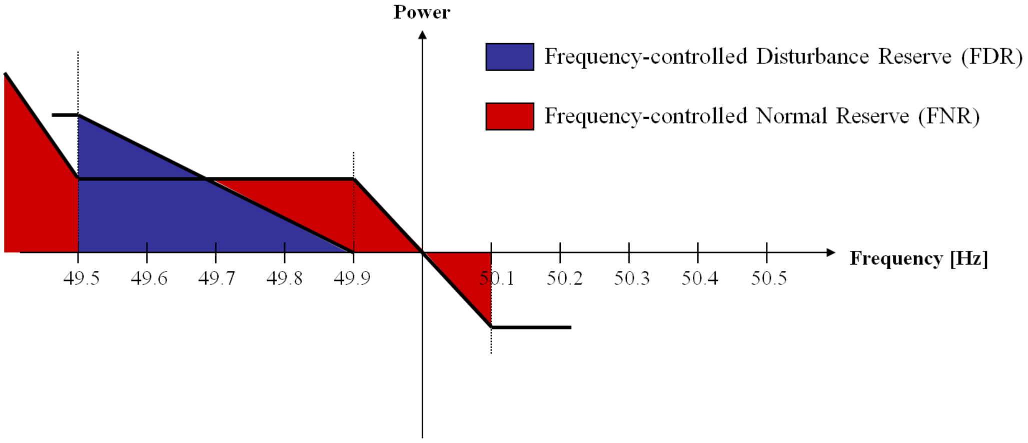

**Figure 2-7: Frequency control in the ENTSO-E RG Nordic power system**

Figure 2-7 does not show the impact of manual reserves. Manual reserves are activated in order to release prior activated FNR and FDR, and they serve the purpose of restoring the system frequency and the scheduled transmission on tie lines.

In chapter 5, frequency control in both Denmark and Germany is analyzed.

### 2.5.3 Decentralized Frequency Control Action

This first frequency control action may commonly be referred to as primary frequency control. However, primary frequency control has different meanings in the ENTSO-E RG Continental Europe and ENTSO-E RG Nordic systems. Primary frequency control defines a specific frequency control action in the ENTSO-E RG Continental Europe power system. Primary frequency control would possibly involve both FNR and FDR in the ENTSO-E RG Nordic system since both FNR and FDR respond with respect to frequency deviations.

Regardless of the power system of interest, the first frequency control action is based on frequency deviations measured locally at power plants. In a large power system, this task is shared by many power plants and, thus, can be regarded to be both decentralized and automated.

This automation is achieved through a turbine governor responding to frequency deviations. The turbine governor uses a signal related to the system frequency, such as the shaft speed, in order to adjust the power output of the plant. Figure 2-8 illustrates schematically such a turbine governor.

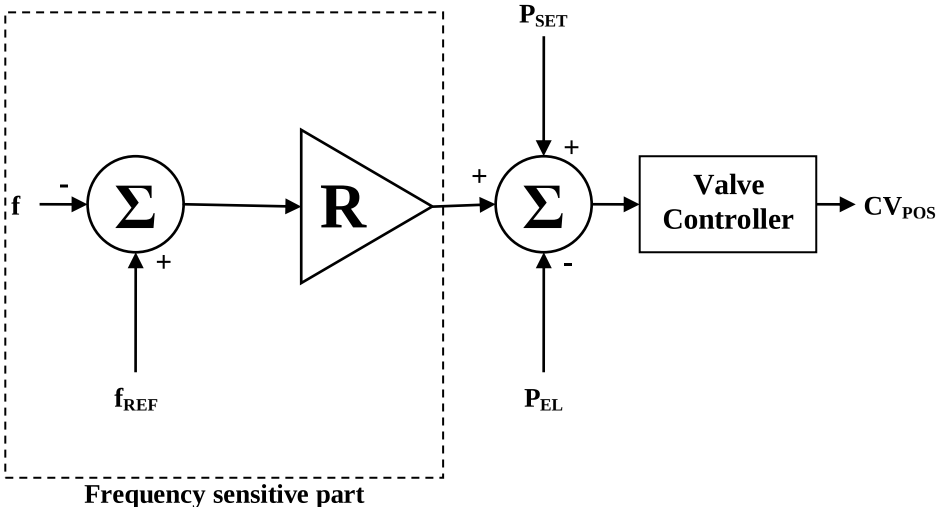

**Figure 2-8: Schematic illustration of a turbine governor**

The frequency deviation is amplified by the inverse of the droop σ, or also commonly referred to as the static.

$$R = \frac{1}{\sigma}$$

The droop determines *"... the steady-state speed versus load characteristics of the generating unit"* [9] and is typically given in $Hz/_{MW}$ or %. This amplification of the frequency deviation gives a signal corresponding to power which is summed with the set value for power output.

The difference between the set value plus the contribution from frequency control and the actual generated power is determined. This power deviation is fed into the valve controller, typically a PI or PID controller, which adjusts the valve position(s) of the control valve(s). This valve position adjustment eventually leads to a change in power output.

It should be noted that this first frequency control action does not restore the frequency to its nominal value. Frequency restoring is the purpose of secondary frequency control actions, which is described in section 2.5.4.

### 2.5.4 Centralized Frequency Control Action

Centralized frequency control is commonly referred to as secondary frequency control. Again, this term is used differently with respect to different power systems. In the ENTSO-E RG Continental Europe power system, secondary frequency control is a defined frequency control action. In the ENTSO-E RG Nordic, secondary frequency control would correspond to the manual power set point change in participating power plant, i.e. the activation of manual reserves.

The purpose of centralized frequency control is: a) to release prior activated reserves for decentralized frequency control action, b) to restore the system frequency to its nominal value and c) to restore the scheduled transmission on tie-lines [11].

In contrary to decentralized frequency control, centralized frequency is usually controlled centrally by the system operator (TSO). The TSO changes the power set point of participating units by sending a control signal to the turbine governor. This additional input signal makes the power generation increase or decrease so that the nominal power system frequency is restored.

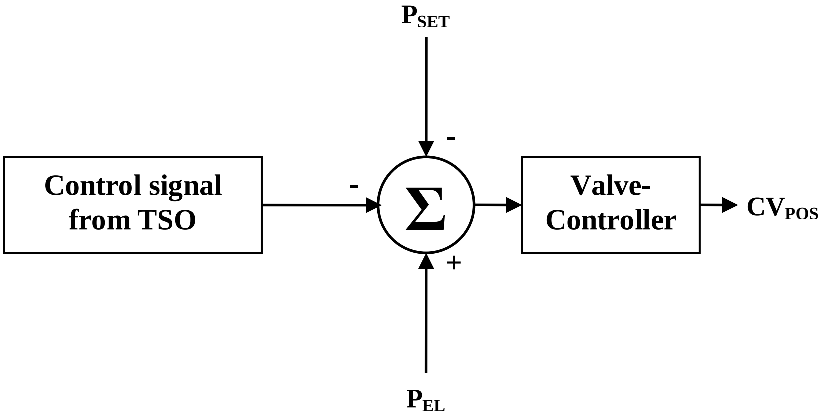

**Figure 2-9: Schematic illustration of secondary control action**

In the ENTSO-E RG Continental Europe power system, tertiary control is also used. Tertiary frequency control is in many ways very similar to secondary frequency control. The only major difference is the larger time delay after which tertiary control is activated, see figure 2-5 and figure 2-6.

# 3 Modeling

## 3.1 Modeling and Simulation Software

All modeling and simulating was performed in the multi-domain simulation tool Dymola which utilizes the open modeling environment Modelica. Modelica is an object-orientated programming language for model development and design. Dymola is used for compiling the model, performing simulations and illustrating the results.

Modelica can be looked at as an object-orientated, equation-based programming language for modeling purposes [3]. Three distinctive features of Modelica are pointed out by the author in [3]:

- Modelica is based on equations instead of assignments. This property allows acausal modeling and flexible reuse of models since the data-flow direction is not predefined.
- Modelica has multi-domain capability. Models from different engineering domains such a mechanical, thermodynamics and electrical can be developed and lumped to an overall model.
- The general class concept permits stepwise development and specialization of models and model-components.

In addition to these points, sharing of models and libraries is comparably easy and many libraries, both free and commercial, are available [14]. A library is generally defined as a collection of models. These models are developed to be used together with other components of the respective library.

Modelica contains a number of standard libraries that provide a solid base for modeling tasks. These libraries provide general, unspecified models that could not cope with the demands for this report. Therefore, two additional, freely available libraries were utilized: `ObjectStab` and `ThermoPower`.

Modelica is designed for modeling systems described by sets of differential-algebraic equation (DAE). Partial differential equations are not yet supported as such, but they may be reduced to ordinary differential equations [15]. The physical origin of the respective equations is not of importance. Thus, Modelica can be utilized to model components from different engineering domains such as thermodynamics, electrical, mechanical, or chemical.

### 3.1.1 Acausality

A number of established multi-purpose simulation tools, such as Simulink, propagate the usage of block diagrams with defined inputs and outputs. The data flow goes from inputs to output and must be defined beforehand [16]. The resulting system of equations can be written as:

$$\begin{aligned} \frac{dx}{dt} &= f\left(x,u\right) \\ y &= g\left(x,u\right) \end{aligned}$$

where, $u$ is the input vector, $x$ is the state vector and $y$ is the output vector.

The development of such a structure can require a lot of mathematical knowledge and may be cumbersome. Furthermore, the system of equations changes each time a component is added to the model or taken away. Thus, reusability of such models is limited.

Modeling in Modelica is done acausal. Thus, the direction of data flow is not unidirectional. The '=' operator does not assign a value to a variable, but defines an equation without settling the direction of data flow [3]. As an example, the equation describing Ohm's law should be considered:

$$U = RI$$

Where, $U$ is a DC voltage, $R$ is an electrical resistance and $I$ is an electrical DC current.

In Modelica, the shown equation does not require the knowledge of the resistance $R$ and the current $I$. It just requires the knowledge of two quantities so that the third quantity can be calculated [16]. Modelica solves automatically for the unknown variable.

### 3.1.2 Differential-Algebraic Equations

Physical processes can generally be described by sets of differential-algebraic equations (DAE). In Modelica, it does not matter where these equations originate from. A set of DAEs may be written in the following form:

$$0 = f\left(\frac{dx}{dt}, x, y, u\right)$$

where, $x$ is the vector of unknowns that appear differentiated in the equation and $y$ is the vector of unknowns that do not appear differentiated [17].

When defining a differential equation in Modelica, the respective state variable(s) can be declared as such. Furthermore, reasonable start values should be provided. When no start values are given, Modelica indicates a warning during the compilation and self defines them. Start values chosen by Modelica may, however, not be physically reasonable. Therefore, it is recommended to set start values manually.

### 3.1.3 The `ObjectStab` Library

The main work on `ObjectStab` was carried out by Mats Larsson during his postgraduate studies at Lund University, Sweden. The library's focus lies on power system stability studies, which are often conducted by using specialized tools such as Simpow, PSS/E or EuroStag. The drawback with these simulation tools lies in their somewhat closed architecture and difficulty to adapt components [18].

`ObjectStab` is designed to provide wide modeling flexibility and modifications on an individual basis. The library comes with a number of predefined components such as generators with different levels of detail, loads, transmission lines and faults. All these components can easily be connected in the graphical editor; no additional code is necessary.

It should be pointed out that no specific load flow calculations are performed. Instead, the initial values for voltages and angles are interpreted as the output from a load flow simulation. The library can be retained from the author Mats Larsson and is free of charge.

### 3.1.4 The `ThermoPower` Library

`ThermoPower` was mainly developed by Francesco Casella, assistant professor at the Dipartimento i Elettronica e Informazione, Politecnico di Milano, Italy. The aim of the library is the dynamical modeling of thermal power plants, and the library's scope is narrower than that of other Modelica libraries for thermo-fluid systems [19].

`ThermoPower` provides a number of components and interfaces, for instance heat exchangers, pipes, boilers, turbines and valves. Models for different fluids, such as water and different gases, are used from the Modelica standard library [20].
The principles for modeling follow to large extent [10] and are based on mass, energy and momentum equations [20].

The library is freely available and licensed by Politecnico di Milano under the Modelica license 2 [21]. The library can be downloaded from [22]. The models utilized later in this report are based on `ThermoPower` version 2.1, released on the 6th of July 2009.

## 3.2 Connectors

A convenient way of connecting components in Modelica is to define connectors, or also called terminals. These connectors define the interface between two components. They can contain two kinds of variables: a) non-flow variables and b) flow variables [3]. Non-flow variables define quantities that remain the same going from one component to another, e.g. voltages or pressure. Flow variables, in contrast, describe a quantity flowing from one component to another, e.g. electrical currents or mass flow. Both kinds of variables can be described with their corresponding physical units.

In the overall model, three different kinds of connector interfaces were used, namely electrical, mechanical and thermo-hydraulic connectors.

Electrical terminals (ET) define voltages, currents and phase angles for electrical components. These connectors are defined with four variables: the real and imaginary parts of both voltage and current.

In `ObjectStab`, they are described as follows [18]:

```
connector Pin "Electrical connector for ObjectStab models"
  Base.Voltage va(start=0) "Real part of voltage";
  Base.Voltage vb(start=0) "Imaginary part of voltage";
  flow Base.Current ia(start=0) "Real part of current";
```

```
  flow Base.Current ib(start=0) "Imaginary part of current";
end Pin;
```

In this project, only positive sequence quantities were simulated, see section 3.13.4.

Mechanical terminals (MT) describe the interaction between rotating mechanical components. These connectors contain two variables: one for torque and one for rotation angle.

In the Modelica standard library, a rotational-mechanical terminal is defined as:

```
connector Flange_a "1-dim. rotational flange of a shaft"
  SI.Angle phi "Absolute rotation angle of flange";
  flow SI.Torque tau "Cut torque in the flange";
end Flange_a;
```

Thermo-hydraulic terminals (THT) are used to connect thermo-hydraulic components such as valves and turbines. Four variables: mass flow rate, temperature, pressure and enthalpy, describe the mutuality between thermo-hydraulic components. As for all thermo-hydraulic components, the THT allows the selection of a suitable medium model.

In the library `ThermoPower`, the interface is given by:

```
connector Flange "Generic flange connector for water/steam flows"
  replaceable package Medium = StandardWater
            constrainedby Modelica.Media.Interfaces.PartialMedium
            "Medium model";

  Medium.AbsolutePressure p "Pressure";
  flow Medium.MassFlowRate w "Mass flowrate";
  Medium.SpecificEnthalpy hAB "Inlet enthalpy";
  Medium.SpecificEnthalpy hBA "Outlet enthalpy";
end Flange;
```

In addition to the three terminals presented, causal Real and Boolean signal connectors were used in order to connect blocks processing real and Boolean variables such as filter blocks. These terminals are attributed with `input` or `output` [3], respectively, and can be compared to the well known connector interfaces in Simulink.

In the graphical editor, it is not possible to connect two different kinds of terminals, i.e. ET and MT.

## 3.3 Synchronous Generator

The synchronous generator was modeled according to a mathematical representation derived in [9], [11]. This representation consists of six differential equations describing the generator’s motion and rotor dynamic. These equations do not account for effects of speed variations on the stator voltage and saturation.

The used equations presented here are adapted for use of per unit values. The $L_{ad}$-base reciprocal per unit system is used for rotor quantities due to its wide acceptance and simplifications [9].

A set of differential equations describing the rotor dynamic is given by:

$$\dot{\delta} = \omega_{el}\omega \tag{3.1}$$

$$\dot{\omega} = \frac{1}{2H}\left(P_m - P_e - D\omega\right) \tag{3.2}$$

where, $\delta$ is the rotor angle of the synchronous generator in electrical radians, $\omega$ is the per unit speed deviation, $\omega_{el}=2\pi f_0$ is the electrical angular frequency, $H$ is the inertia constant, $P_m$ is the mechanical power, $P_e$ is the electrical power and $D$ is a damping coefficient. The fluxes on the d- and q-axis are calculated as:

$$\dot{\Psi}_{fd} = \omega_{el}\left(e_{fd} + \frac{\left(\psi_{ad} - \psi_{fd}\right)R_{fd}}{L_{fd}}\right) \tag{3.3}$$

$$\dot{\Psi}_{1d} = \omega_{el}\left(\frac{\psi_{ad} - \psi_{1d}}{L_{1d}}\right)R_{1d} \tag{3.4}$$

$$\dot{\Psi}_{1q} = \omega_{el}\left(\frac{\psi_{aq} - \psi_{1q}}{L_{1q}}\right)R_{1q} \tag{3.5}$$

$$\dot{\Psi}_{2q} = \omega_{el}\left(\frac{\psi_{aq} - \psi_{2q}}{L_{2q}}\right)R_{2q} \tag{3.6}$$

where, $\psi_{fd}$ is the field flux, $e_{fd}$ is the field voltage, $\psi_{ad}$ and $\psi_{aq}$ are the d- and q-axis mutual flux linkages, $L_{fd}$ is the field inductance, $R_{fd}$ is the field resistance, $L_{1d}$, $L_{1q}$ and $L_{2q}$ are the respective d- and q-axis amortisseur inductances, $R_{1d}$, $R_{1q}$ and $R_{2q}$ are the respective d- and q-axis amortisseur inductances and $\psi_{1d}$, $\psi_{1q}$ and $\psi_{2q}$ are the respective d- and q-axis amortisseur fluxes.

In short, it is illustrated below how these six equations, describing the rotor dynamics, are written in Modelica.

```
// Defining equations given that all used variables are declared
  der(delta) = ws*(w - wref);
  der(w) = 1/(2*H)*(Pm - Pe - D*(w - wref));
  der(lamfd) = ws*((Efd*Rfd/Ladu) + (lamad - lamfd)*Rfd/Lfd);
  der(lam1d) = ws*(lamad - lam1d)/L1d*R1d;
  der(lam1q) = ws*(lamaq - lam1q)/L1q*R1q;
  der(lam2q) = ws*(lamaq - lam2q)/L2q*R2q;
// Setting initial values
initial equation
  delta = 0;
  w = 1;
  der(lamfd) = 0;
  der(lam1d) = 0;
  der(lam1q) = 0;
  der(lam2q) = 0;
```

where, the operator `der()` defines a first order derivative with respect to time.

Additionally, the following set of algebraic equations is included in the model of the synchronous generator.

$$\psi_{ad} = L''_{ads}\left(-i_d + \frac{\psi_{fd}}{L_{fd}} + \frac{\psi_{1d}}{L_{1d}}\right) \tag{3.7}$$

$$\psi_{aq} = L''_{aqs}\left(-i_q + \frac{\psi_{1q}}{L_{1q}} + \frac{\psi_{2q}}{L_{2q}}\right) \tag{3.8}$$

with

$$L''_{ads} = \frac{1}{\frac{1}{L_{ads}} + \frac{1}{L_{fd}} + \frac{1}{L_{1d}}}$$

$$L''_{aqs} = \frac{1}{\frac{1}{L_{aqs}} + \frac{1}{L_{1q}} + \frac{1}{L_{2q}}}$$

$$L_{ads} = K_{sd} L_{adu}$$

$$L_{aqs} = K_{sq} L_{aqu}$$

where, $\psi_{ad}$ and $\psi_{aq}$ are the d- and q-axis air-gap (mutual) flux linkages, $i_d$ and $i_q$ are the d- and q-axis currents, $L''_{ads}$ and $L''_{aqs}$ are the d- and q-axis saturated sub-transient mutual inductances, $L_{ads}$ and $L_{aqs}$ are the d- and q-axis saturated mutual inductances, $L_{adu}$ and $L_{aqu}$ are the d- and q-axis unsaturated mutual inductances and $K_{sd}$ and $K_{sq}$ are the d- and q-axis saturation coefficients. $K_{sd}$ and $K_{sq}$ are both set to be one, i.e. no saturation is considered.

The stator and rotor flux linkages are given by

$$\psi_d = -L_l i_d + \psi_{ad} \tag{3.9}$$

$$\psi_q = -L_l i_q + \psi_{aq} \tag{3.10}$$

where, $\psi_d$ and $\psi_q$ are the d- and q-axis flux linkages and $L_l$ is the leakage inductance.

The representation of the d-axis is shown in figure 3-1.

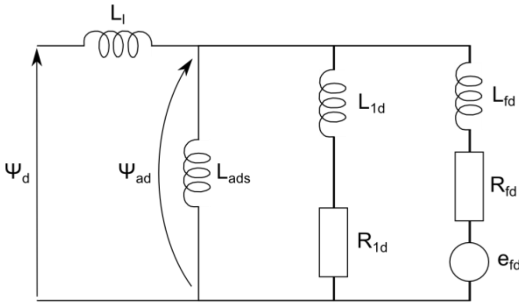

**Figure 3-1: Representation of the d-axis [9]**

The representation of the q-axis is shown in figure 3-2.

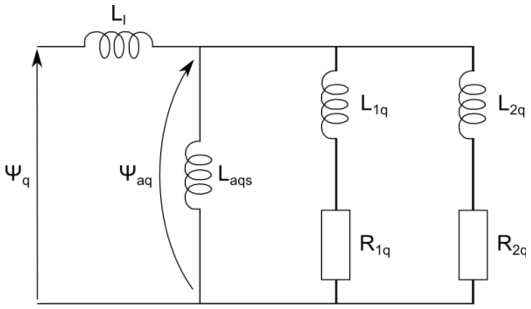

**Figure 3-2: Representation of the q-axis [9]**

The stator equations are given by

$$E_d = -R_a i_d + \omega_{el} L_q'' i_q + E_d'' \tag{3.11}$$

$$E_q = -R_a i_q - \omega_{el} L_d'' i_d + E_q'' \tag{3.12}$$

$$E_d'' = -\omega_{el} L_{aqs}'' \left( \frac{\psi_{1q}}{L_{1q}} + \frac{\psi_{2q}}{L_{2q}} \right) \tag{3.13}$$

$$E_q'' = -\omega_{el} L_{ads}'' \left( \frac{\psi_{fd}}{L_{fd}} + \frac{\psi_{1d}}{L_{1d}} \right) \tag{3.14}$$

with

$$L_d'' = L_l + L_{ads}''$$
$$L_q'' = L_l + L_{aqs}''$$

where, $E_d$ and $E_q$ are the d- and q-axis voltages, $R_a$ is the armature resistance, $L''_d$ and $L''_q$ are the d- and q-axis sub-transient inductances and $E''_d$ and $E''_q$ are the d- and q-axis sub-transient voltages.

The rotor equations above are given in generator orthogonal coordinates, i.e. in the d-q reference frame. The equations for the terminal voltages $U_a$ and $U_b$ are, in contrast, given in the network a-b reference frame. The relationship between these two coordinate systems is given by Kron’s transformation [11]:

$$\begin{bmatrix} E_d \\ E_q \end{bmatrix} = \begin{bmatrix} -\sin(\delta) & \cos(\delta) \\ \cos(\delta) & \sin(\delta) \end{bmatrix} \begin{bmatrix} U_a \\ U_b \end{bmatrix} \tag{3.15}$$

where, $U_a$ and $U_b$ are the real and imaginary part of the terminal’s positive sequence voltage. In a similar manner, it is possible to transform real and imaginary parts of the currents.

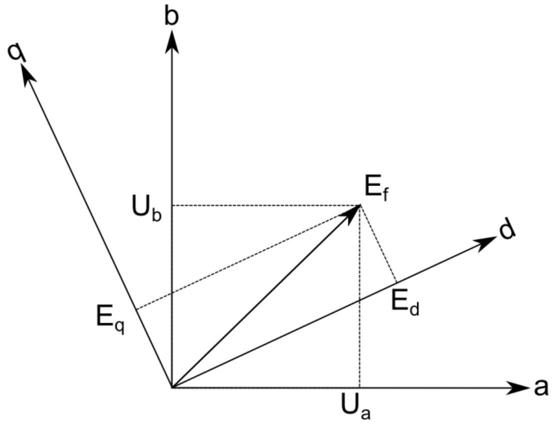

**Figure 3-3: Transformation from a-b to d-q reference frame [9] [11]**

This transformation gives each generator its own d-q coordinate system.

The generated electrical power is given by

$$P_{el} = \omega_{el}\left(\psi_{ad} i_d + \psi_{aq} i_q\right) \tag{3.16}$$

Connecting the turbine and the generator, the mechanical power conveyed via the shaft, see section 3.13.5, is given by:

$$P_m = \tau_m \omega_m = \tau_m \frac{d\phi_m}{dt} \tag{3.17}$$

The quantities in the turbine model are given in physical units, whereas the generator is described in per unit. In order to make these two models compatible, the mechanical power is divided by the rated power of the turbine.

The generator model contains a simple model of the step-up transformer. The step-up transformer can be described by a static resistance and impedance. The power plants internal consumption is modeled by a static, purely active power load.

All data used for the generator is based on [23].

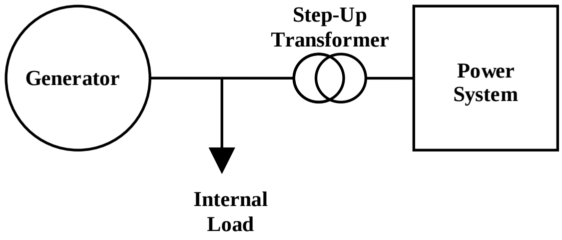

**Figure 3-4: Schematic illustration of the generator model**

## 3.4 Steam Turbine

A steam turbine with different pressure levels can be modeled as an aggregated cascade of turbine sections. Each turbine section is defined by its respective in- and outlet quantities such as temperature, pressure and specific enthalpy. The following equations are given for use in SI units.

Given the in- and outlet pressure and the steam density in a turbine section, the mass flow rate can be calculated according to Stodola's law [24].

$$\omega_{Turb} = k_T \sqrt{\rho_i p_i} \sqrt{1 - r_s^2} \tag{3.18}$$

where, $\omega_{Turb}$ is the mass flow rate through the turbine, $\rho_i$ is the density of the inlet steam, $p_i$ is the inlet pressure, $r_s = {}^{p_o}\!/_{p_i}$, with $p_o$ being the outlet pressure, and $k_T$ is the Stodola coefficient. The coefficient $k_T$ can be determined from geometrical or experimental data, has the unit [m$^2$] (square-meters) and may be different for each turbine section [10].

The energy equation is given by

$$h_i - h_o = \left(h_i - h_{ISO}\right)\eta_{ISO} \tag{3.19}$$

where, $h_i$ is the inlet enthalpy, $h_o$ is the outlet enthalpy, $h_{ISO}$ is the enthalpy that would be at the outlet if the expansion were iso-entropic and $\eta_{ISO}$ is the iso-entropic turbine section efficiency.

The determination of the iso-entropic efficiency $\eta_{ISO}$ is described in 0. For loads above 20 % of the nominal load, the iso-entropic efficiency can be regarded as constant [10].

Given the mass flow rate and the values for the in- and outlet enthalpy, the mechanical power on the shaft can be calculated.

$$P_m = \eta_m \omega_{Turb} \left(h_i - h_o\right) \tag{3.20}$$

where, $\eta_m$ is the mechanical efficiency.

The mechanical torque is then

$$\tau_m = \frac{P_m}{\omega_m} \tag{3.21}$$

where, $\omega_m$ is the mechanical angular speed of the turbine shaft.

## 3.5 Control Valves

Two control valves were included in the model. The control valve at the high pressure turbine stage and the control valve at the intermediate turbine pressure turbine were included in the model, compare figure 2-4.

The mass flow rate through a valve can be described as [10]:

$$\omega_{Valve} = F_p\left(\theta\right) A_v Y \sqrt{\rho_i p_i r_s} \tag{3.22}$$

where, $F_p(\theta)$ describes the piping geometry with respect to the valve position $\theta$, $A_v$ is the valve sizing coefficient, $Y$ is the compressibility factor, $\rho_i$ is the inlet steam density, $p_i$ is the inlet steam pressure and $r_s$ is the pressure drop ratio.

The characteristic of the valve model was assumed to be linear. This assumption implies that the mass flow rate through the valve $\omega_{Valve}$ is linearly dependent on the valve position $\theta$.

The valve sizing coefficient $A_v$ is given as an area in [m$^2$] (square-meters) and can be compared to the Stodola coefficient $k_T$ in (3.18).

## 3.6 Boiler, Re-heater and Condenser

The boiler was modeled as an ideal steam source which is defined by reference values for pressure and temperature. These reference values are stored in tables. By linear inter- and extrapolation, values between or outside the reference values are determined.

The re-heater between high pressure turbine and intermediate pressure turbine was assumed to be ideal. This model causes an increase in specific enthalpy and decrease in steam pressure according to reference data stored in a table.

The condenser was, in analogy to the boiler, modeled as an ideal steam sink. Reference values for pressure and temperature are stored in a table. The condenser model provides three steam sinks: one for the outlet of the high pressure turbine, one for the major steam extraction at the intermediate pressure turbine and one for the outlet of the intermediate pressure turbine.

The boiler model, re-heater model and condenser model require a power set point as an input signal and are based on data provided in [25].

## 3.7 Overall Steam Cycle

Steam turbines usually consist of several turbine stages such as high pressure, intermediate pressure and low pressure. Some turbines are even equipped with a very-high pressure stage. Furthermore, each of these stages may have several steam extractions.

A complete steam turbine with its respective stages and steam extractions can be modeled as an aggregated cascade of steam turbine models. Each individual section model must be defined by parameters such as mechanical and iso-entropic efficiency, the Stodola coefficient and nominal inlet and outlet quantities such as pressure and temperature.

The boundaries are described by thermo-hydraulic terminal (TH) and mechanical terminals (MT) [10]. Figure 3-5 shows these boundaries given by connectors used in Modelica.

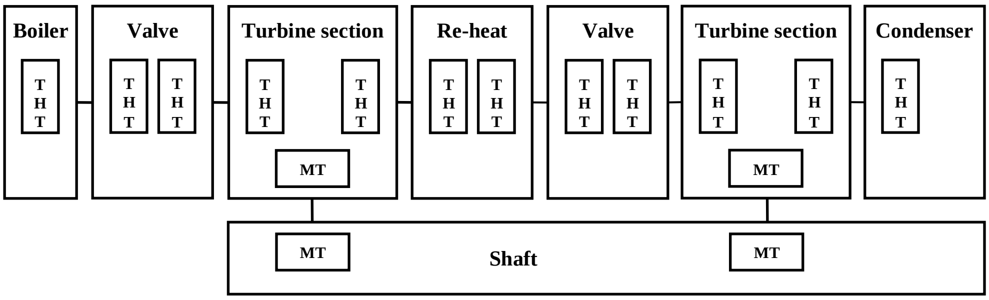

**Figure 3-5: Schematic representation of the steam cycle model with interconnectors (inspired by figure 2.5 in [10])**

The steam turbine was modeled as an aggregated cascade of three turbine sections, namely high pressure (HP), intermediate pressure one (IPT1) and intermediate pressure 2 (IPT2). In addition, control valves at both the inlet of the high pressure turbine section and the intermediate turbine pressure section were included. Such a turbine configuration is the real case at Amagerværket Block 1 in Copenhagen, Denmark, compare figure 2-4.

## 3.8 Excitation System and Power System Stabilizer

The excitation system of a synchronous generator controls the field voltage in the rotor. This property allows controlling the terminal voltage at the generator bus. Furthermore, reactive power production or consumption of the generator can be regulated. A general illustration of an excitation system is given in figure 3-6 below.

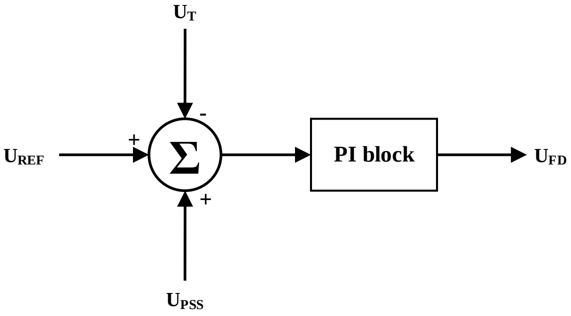

**Figure 3-6: Illustration of the automatic voltage regulator**

where, $U_{ref}$ is the reference voltage, $U_T$ is the actual terminal voltage, $U_{PSS}$ is the PSS output voltage and $U_{FD}$ is the field voltage.

The excitation system is equipped with a power system stabilizer (PSS). The purpose of a PSS is to damp power oscillations at a frequency range from 0.1 to 2 Hz by modulating the field voltage.

The PSS used here is of type PSS3B according to the IEEE 412.5 standard but with an additional field current branch. The input signals are active power *P*, electrical frequency *f* and field current $I_f$. Figure 3-7 shows the model of the PSS schematically.

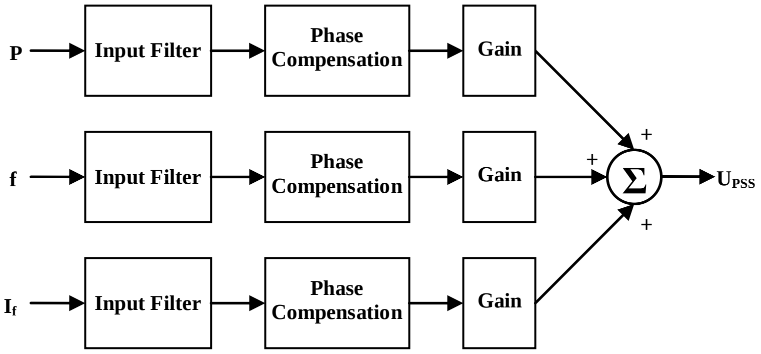

**Figure 3-7: Illustration of the power system stabilizer**

In order to complete the model of the excitation system, the PSS was included but is by default deactivated due to the component's minor role in the conducted simulations.

## 3.9 Turbine Governor

The governor regulates the output power of the steam turbine by means of controlling the valve position at the inlet of both the high pressure and intermediate turbine section. Figure 3-9 illustrates the turbine governor model.

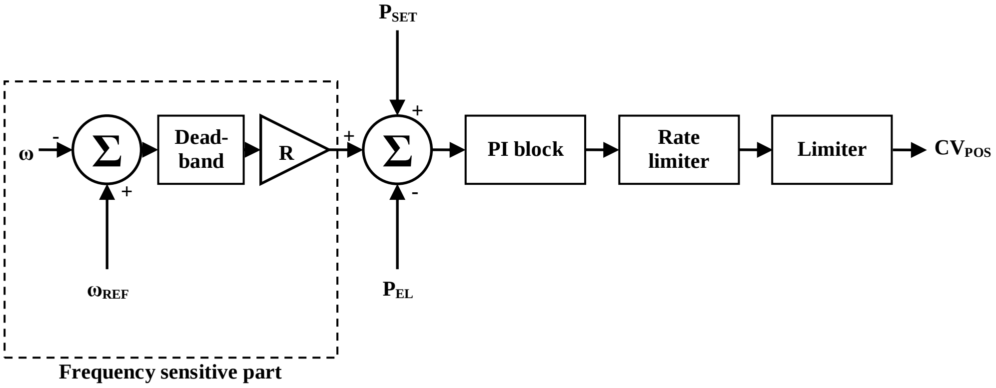

**Figure 3-8: Illustration of the turbine governor**

The governor model uses reference values for load $P_{SET}$ and frequency $\omega_{REF}$. In addition, the model utilizes two input signals: instantly generated electrical power $P_{EL}$ and rotor speed $\omega$. The only output is the control valve position $CV_{POS}$.

The instantly generated electrical power is compared with the power set point. Any deviation is amplified and integrated in a PI controller. The rate limiter restrains both positive and negative changes per time interval, i.e. the deviation of the signal. Finally, the signal leaving the rate limiter is limited to the allowed minimal and maximal valve position.

The frequency sensitive part indicated in figure 3-8 becomes active when the system frequency, and therewith the rotor speed ω, deviates. This deviation is captured by the governor and subjected to a dead-band filter. Then, the deviation is amplified by the gain $R$, which is defined as the inverse of the droop $\sigma$, see section 2.5.3. This amplification causes a virtual change the power set point.

Depending on the frequency deviations sign and amplitude, the governor adjusts the valve position by virtually opening or closing the control valves.

The output signal is fed into the steam turbine where it is separated into two valve positions: one for the HPT control valve and one for the IPT control valve. This separation follows the positioning patterns shown in figure 3-11.

### 3.10 Turbine-Generator Shaft

The turbine-generator shaft was modeled with the inertia model in Modelica, which is given by the following differential equations:

$$\frac{d\varphi_m}{dt} = \omega_m \tag{3.23}$$

$$J\frac{d\omega_m}{dt} = \tau_m \tag{3.24}$$

where, $\varphi_m$ is the shaft angle, $\omega_m$ is the angular shaft speed, $J$ is the moment of inertia and $\tau_m$ is the mechanical torque.

### 3.11 Overall Model

The overall model is assembled of all the components described above:

- Heat source and heat sink accounting for the steam supplying and cooling facilities
- Steam turbine with a high-pressure and an intermediate-pressure stage and respective control valves
- Synchronous generator with its step-up transformer and the power plant’s internal consumption
- Excitation system with automatic voltage regulator (AVR) and power system stabilizer (PSS)
- Turbine governor to control output power via the position of the control valves
- Turbine-generator shaft

The overall model is shown schematically in figure 3-9. For simplicity, just one turbine section and one valve are shown.

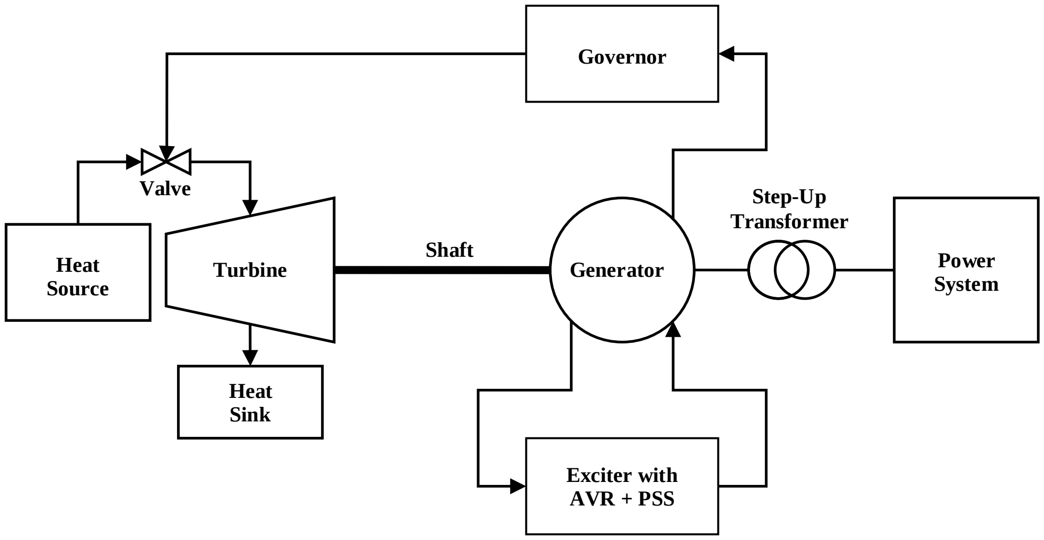

Figure 3-9: Schematic representation of the overall model

For the different simulations, the power system was changed to the respective system configuration, see chapter 4.

Figure 3-10 illustrates the overall model taking into account connectors used in Modelica.

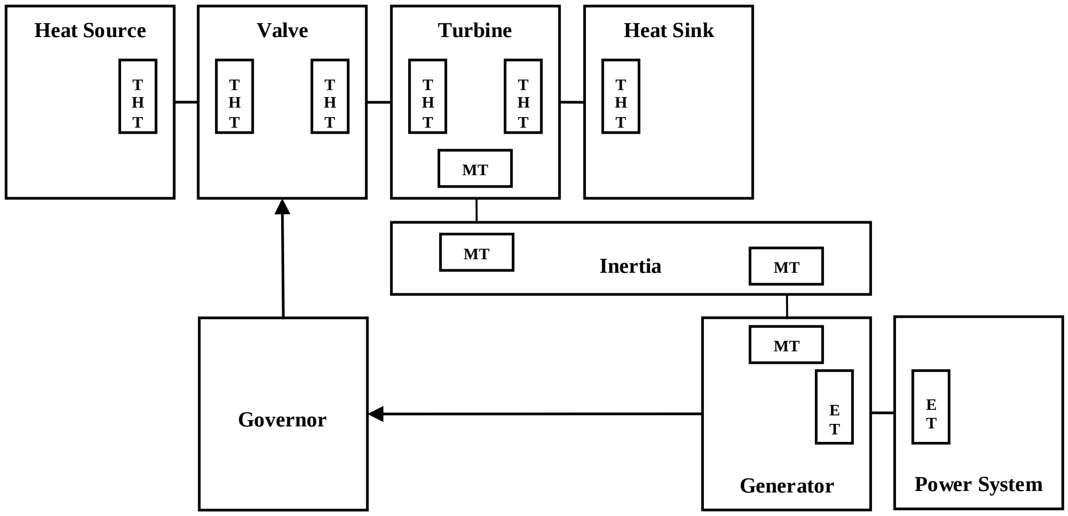

Figure 3-10: Schematic illustration of the overall model with interconnectors

## 3.12 Boundary Conditions

The electrical boundary conditions are given by the system frequency and terminal voltage. A minimal and maximal value for the system frequency was defined. The generator’s terminal voltage and electrical power cannot be negative.

The mechanical rotational shaft speed is always equal to the electrical rotor speed.

The boundary conditions for steam are defined in the models for heat source and heat sink. Both the heat source and heat sink models calculate the respective steam properties according to a power set point. The correlation between power set point and steam properties is given by reference data from the turbine manufacturer given in [25].

The valve positions are limited to minimal and maximal values. In addition, valve positions are restricted to minimal and maximal step changes per time interval, i.e. they are rate limited.

## 3.13 Simplifications within the Model

Modeling an entire thermal power plant in detail would exceed the goal of this project. Therefore, the effort towards modeling was limited to components which were considered most important for the overall aim of the model - the simulation of primary frequency control. Simplifications within the model are listed and described below.

### 3.13.1 Steam Cycle

The steam cycle was not modeled in detail. In particular, this simplification implies that there are no models for pre-heaters, pumps, feed water tanks and pipes. Thus, the model does not represent a closed steam cycle. There are two main reasons for this simplification:

- Time constants of boiler, pre-heaters and condensers are usually in the order of several seconds to minutes. With respect to primary frequency control, these time constants appear to be very large, and, thus, do not play a significant role.
- A high effort towards collecting data for models, e.g. geometrical data, hydraulic resistance and roughness, would be necessary in order to get a complete picture of the entire steam cycle. This data collection would exceed the frame of this project.

Instead of modeling the entire steam cycle, a heat source and a heat sink, respectively, were defined. Pressure and temperature of these two models is determined by the desired output power, which is given as an input parameter to the model.

The model of the steam cycle does not contain any dynamics. Since no volumes, such as in pipes or the boiler, are considered, the steam cycle is described by only algebraic equations.

### 3.13.2 Governor

The governor controls turbine valves (see section 3.13.3 below), ancillary control loops and several safety components in form of limiters and gradients. Ancillary controllers, such as speed controller for island operation, and various safety components were neglected. The governor controls exclusively the turbine control valves.

The valve positioning in real plants depends also on the mode of operation, see section 2.3. In the derived model for Amagerværket Block 1, the different valve control patterns for different modes of operation are not considered. Instead, the patterns shown in figure 3-11 are used for the valve positioning.

### 3.13.3 Valves and Valve Characteristics

Steam cycles in thermal power plants contain a number of valves for different purposes, e.g. turbine-control-, bypass- and safety-valves. Some of these valves are installed for safety reasons and steam utilization other than driving the turbine. Such safety and bypass valves were not considered in the model.

At Amagerværket Block 1, the inlet valve to the high pressure turbine section consists physically of four valves. Two of them are controlled in parallel, whereas the remaining two are controlled separately [26]. This control pattern is shown in figure 3-11.

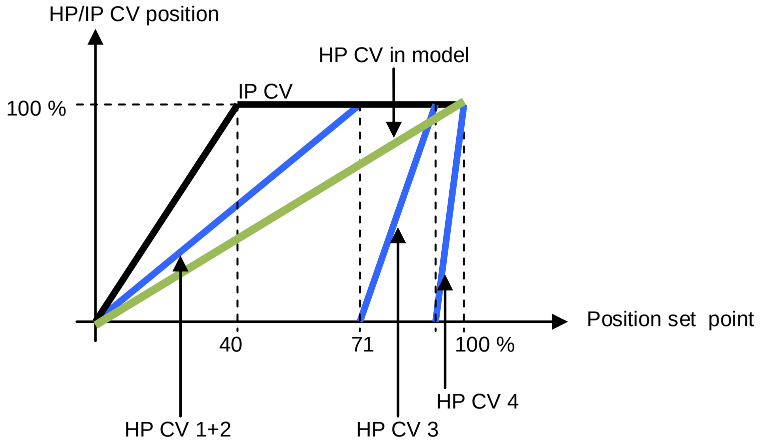

**Figure 3-11: Ideal turbine valve positions as a function of the position set point [26]**

In figure 3-11, *HP* and *IP* stand for high pressure and intermediate pressure, respectively, and *CV* for control valve. The ‘Position set point’ on the x-axis is the governor output signal $CV_{POS}$, see section 3.9.

In figure 3-11, the blue curves show the valve positioning at the four physical high pressure turbine control valves installed at Amagerværket Block 1. The green curve indicates the valve position of the fictional valve used in the model. The black curve shows the valve position of the valve mounted at the intermediate pressure turbine. This curve is also used in the model.

The four valves mounted on the high pressure turbine were joined into one fictional, single valve. Four valves in parallel caused the solver in Dymola to quit with an error message saying that no solution could be found. The fictional valve’s characteristic was assumed to be linear.

The characteristic of the valve mounted at the intermediate pressure turbine was modeled according to figure 3-11.

Consequently, these two valves are the only means for the governor to control the power output from the turbine, and no steam bypassing was taken into account.

Possible effects and time delays of servo motors opening and closing valves were not considered in the model.

### 3.13.4 Electric Grid

The generator, together with the grid, is assumed to operate perfectly symmetrically. This assumption means that just positive-sequence quantities and no negative- or zero-sequence quantities are taken into account. This simplification allows solving for just one sequence component instead of three sequence components [9].

The transformation from three phase components to symmetrical components is given by the transformation matrix $\mathbf{T_s}$ [9]:

$$\mathbf{T_S} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \tag{3.25}$$

Its inverse is given by:

$$\mathbf{T_S}^{-1} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \tag{3.26}$$

where, $\alpha = e^{j120^\circ}$. For instance, the voltages can then be transformed as follows:

$$\mathbf{U_s} = \mathbf{T_S}^{-1}\mathbf{U_{abc}}$$

where, $\mathbf{U_s}$ is a vector containing the zero-, positive- and negative-sequence voltages $\overline{U_0}$, $\overline{U_1}$ and $\overline{U_2}$, and $\mathbf{U_{abc}}$ is a vector containing the three phase voltages $\overline{U_a}$, $\overline{U_b}$ and $\overline{U_c}$.

The transformation gives that the positive-sequence component has the same phase sequence as the three phase system [9], since the three phase system is symmetric.

Along with voltages, phase currents and impedances given in an impedance matrix can be transformed into symmetrical components as well.

In addition to purely symmetrical conditions, no harmonics are considered either. That is, electrical quantities such as voltages and currents follow an ideal sine wave and do not carry any frequency components other than the nominal frequency.

### 3.13.5 Turbine-Generator Shaft

It was assumed that the rotor speed in the generator is always equal to the shaft speed, i.e. $\omega_m = \omega_e$. Furthermore, the losses in the bearings along the shaft were considered to be constant. Since shaft speed deviations lie approximately in the range of ±20 rpm, this assumption was considered to be good enough for the aim of this project.

### 3.13.6 Fuels

Modern thermal power plants can often run on different fuels such as oil, coal and biomass. Different fuels have different heat content capacities and, thus, affect the steam generation. In addition, the fuel to air ratio may be different for different fuels in order to obtain proper combustion (see section 2.2.1).

The usage of different fuels results in different control reference curves for pressure and temperature. In this report, just one reference curve was used.

## 3.14 Simulation and Visualization

The models presented here were developed in Modelica version 3.1 and compiled and simulated in Dymola version 7.4. The simulation output data were, due to the richer formatting options for graphical plots, exported to and plotted in MATLAB 2009b (version 7.9.0.529).

The models derived and tested here are stored in an additional library named '`Amagerverket`'. This library also requires the libraries `ObjectStab` and `ThermoPower`.

# 4 Simulation and Results

This chapter describes the conducted simulations and summarizes the obtained results.

In the following paragraphs, the term open-loop indicates that the frequency sensitive part of the turbine governor, indicated in figure 3-8, was not active and the output power was not controlled by means of frequency deviations[3].

Parameters for all simulations are given in 0.

Three simulations with different aims were performed.

1. An open-loop test with a defined increase of the power set point at the governor. The simulation's goal was to study the short-term response capability of the model. The simulation results were compared with data which was measured during tests conducted at Amagerværket Block 1.

2. An open-loop test with a time varying power set point signal with the aim to study the long time behavior of the model. The simulation outcomes were compared with measured data from Amagerværket Block 1.

3. The system frequency response following the loss of a major production unit in the ENTSO-E RG Nordic system was simulated. It was then observed how Amagerværket responded to such an event. No recorded data for comparisons were available.

## 4.1 Open-Loop Test 1

In this test, the electric grid outside the power plant is represented by an infinite bus. Thus, the system frequency and voltage at the infinite bus are consequently held at their nominal values. A schematic illustration of the test system is given in figure 4-1.

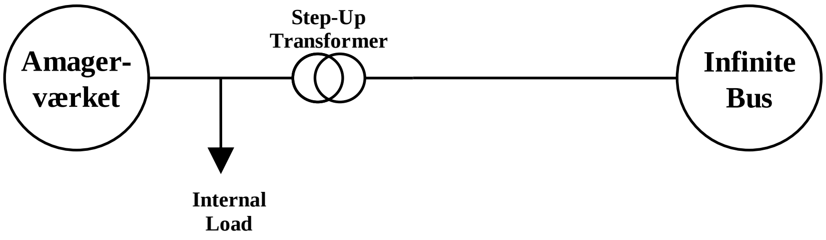

**Figure 4-1: Single machine infinite bus model for open-loop simulation**

Amagerværket is provided a load set point. Starting from a steady-state situation, a positive, step-like ramp is applied to the set point for power output to the governor. The power is then expected to increase by means of valve opening. However, properties of in- and outlet steam of both heat source and heat sink are not changed.

---

[3] Due to the appearance of infinite buses in the test systems for both open-loop simulations, the frequency is permanently kept its nominal value. Thus, the frequency sensitive part of the governor would not affect the simulation results.

The simulation result is compared with measured data from tests conducted at Amagerværket 2011-04-15 between 6 and 8 pm. This comparison is illustrated in figure 4-2 which shows the reference signal (blue curve), the measured electrical power (green curve) and the simulated electrical power (red curve). The reference signal starts to increase its value after 3 seconds based on the time scale used in the plot. The base system power was equal with the base machine power.

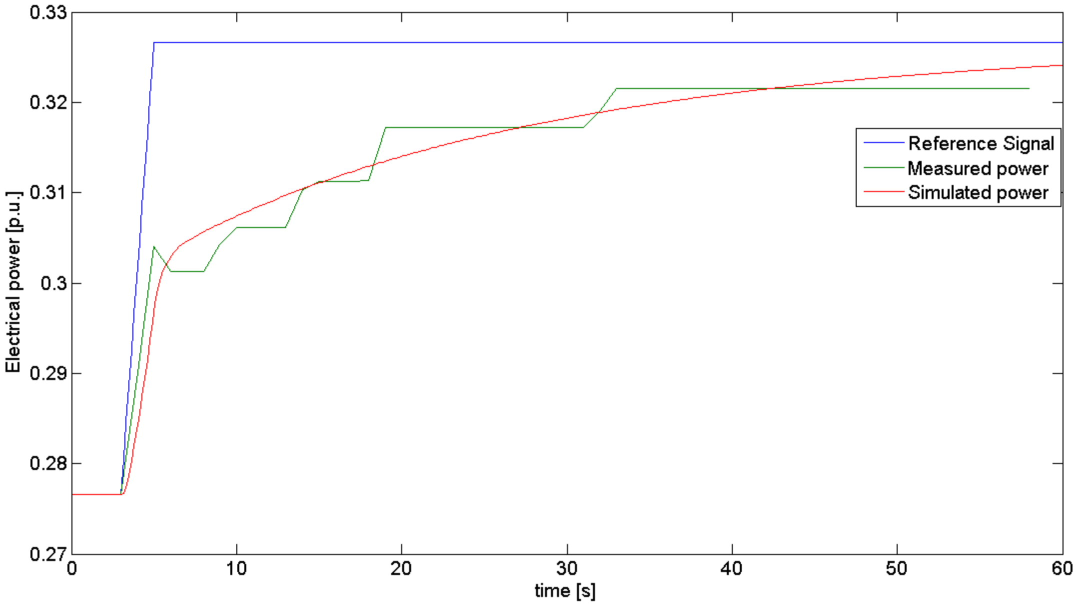

**Figure 4-2: Electrical power after a power set-point increase**

The reference signal is the same for the simulation and the real test. The applied reference signal describes a ramp-like increase of 0.05 p.u. over 2 seconds; see the blue curve in figure 4-2.

From figure 4-2, it can be seen that the simulated response in electrical power (red curve) is quite close to the measured response in electrical power (green curve). During the measurements, however, the bypass valves at high pressure turbine and intermediate pressure turbine were somewhat opened, and these bypass valves are not considered in the model. In addition, the power plant was fired with biomass. This choice resulted in changed steam properties which are not captured by the model. Nevertheless, in spite of these differences, the model captures the real response surprisingly well.

## 4.2 Open-Loop Test 2

In this simulation, a power set point signal from Amagerværket Block 1 was directly fed into the model. This signal provided the set value for electrical power output for a 24 hour period from 2010-11-24 12 am to 2010-11-25 12 am. The measured data is extracted from a database with a sampling time of 1 minute.

During the entire period, the bypass valves at Amagerværket were fully closed. Thus, the only means of regulating the steam flow through the turbine were the turbine control valves and the firing in the boiler.

The test system was exactly the same as in the previous section with the base system power being equal to the base machine power.

Figure 4-3 shows the simulated power, measured power and the reference signal for electrical power output over time. Taking into account the large time range, the simulation follows the measured data rather well.

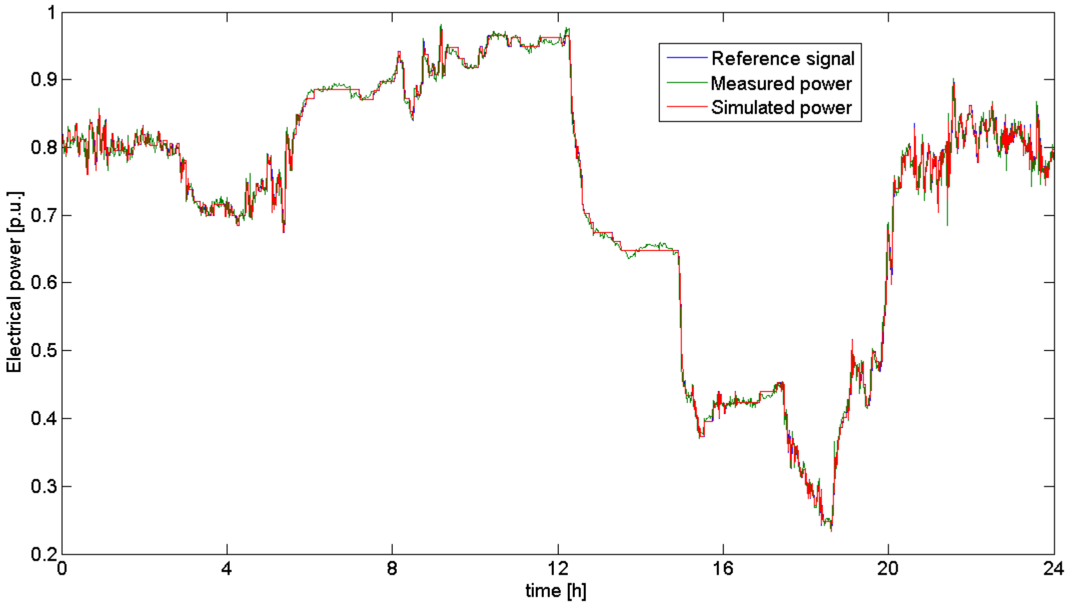

Figure 4-3: Electrical power over time

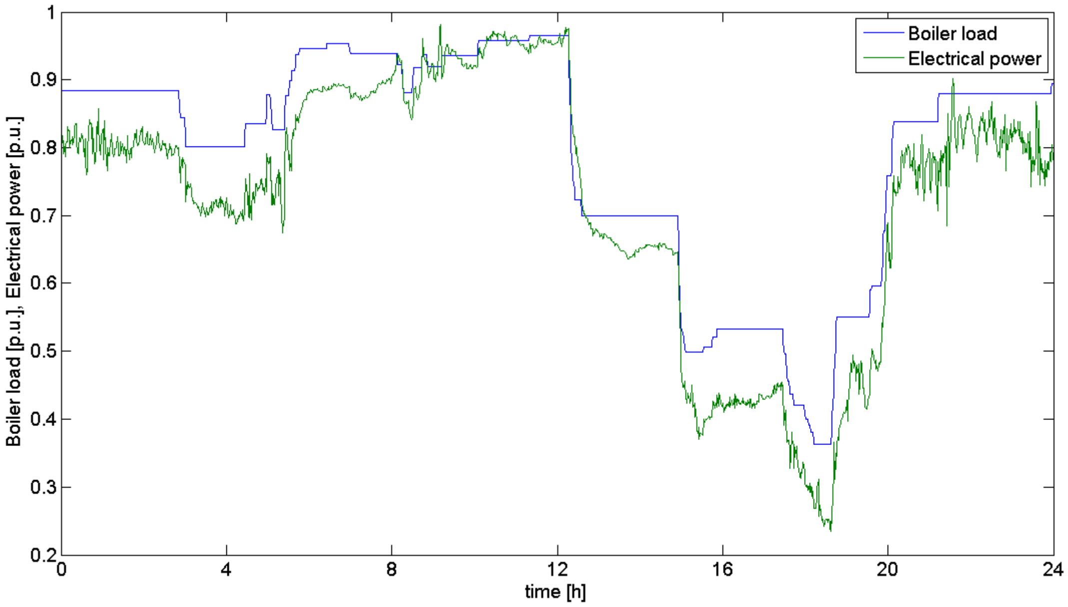

Figure 4-4: Boiler load and electrical power over time

Figure 4-4 shows the boiler load and electrical power over time. It illustrates the correlation between boiler load and electrical power output when bypass valves are closed, i.e. the patterns of both boiler load and electrical power are similar.

Figure 4-5 shows the mass flow rate into the high pressure turbine over electrical power output. The linear relation of these two quantities can be observed from both measured data and simulated data. The simulated mass flow rate lies about 10 kg/s lower with respect to the measured values. The reason for this discrepancy lies mainly in simplifications in valve modeling. Either the valve is not opened wide enough or its nominal mass flow rate is too low.

The slight bend in mass flow rate at around 0.8 p.u. electrical power is a result from the used steam reference curves. At this bending point, the steam reference curve reaches is upper pressure limit, and the pressure in the boiler does not increase any further. This circumstance causes a less steep increase of the mass flow rate. However, this bend is shown in both measured and simulated mass flow rate and, thus, is also present in the physical plant.

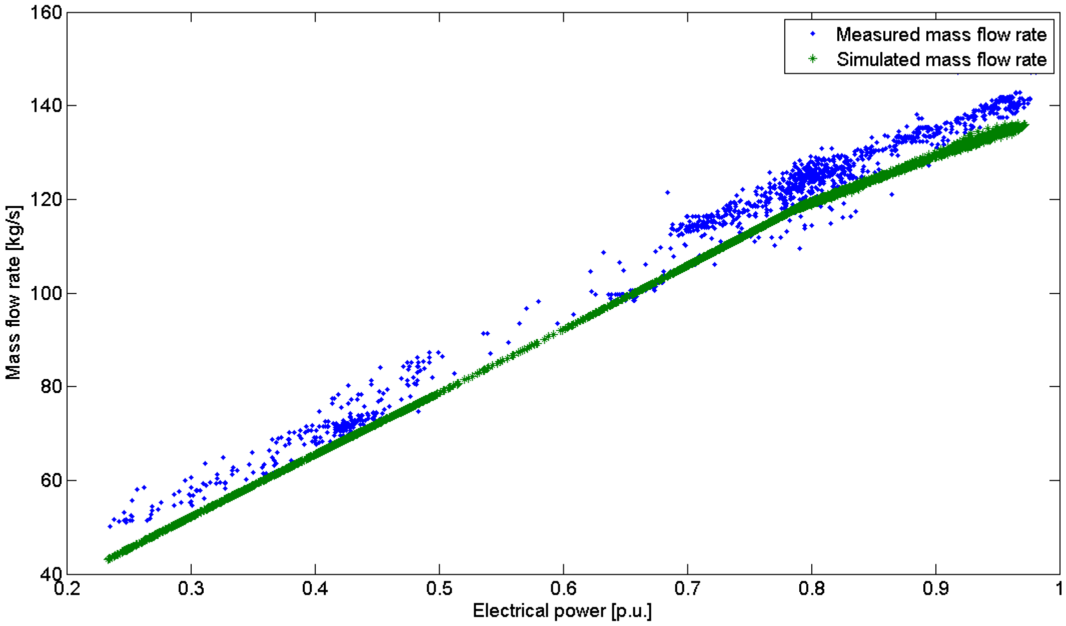

**Figure 4-5: Mass flow rate over electrical power**

In figure 4-6, relevant pressure levels are shown, and, in figure 4-7 corresponding temperature levels are illustrated. The three levels shown describe: a) the high pressure turbine inlet steam, b) the intermediate pressure turbine inlet steam and c) the intermediate pressure turbine outlet steam.

Both pressure and temperature values show a tight correlation between measured and simulated values. The apparent difference may be caused by incomplete and simplified valve models and valve positioning. However, a rather large difference in temperature at the intermediate pressure turbine inlet can be observed, see second plot in figure 4-7. This difference may be caused by simplifications in the re-heater model.

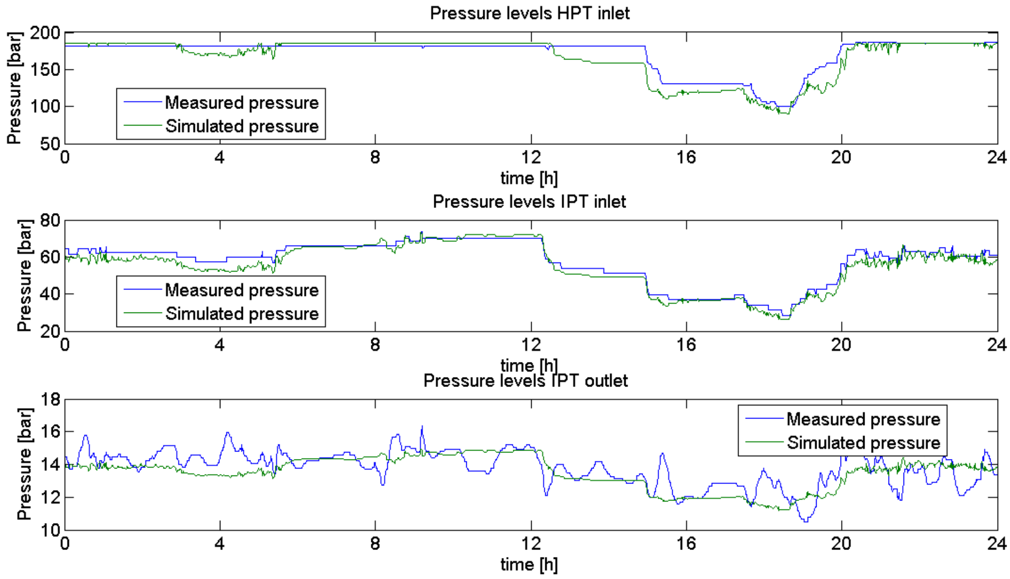

**Figure 4-6: Pressure levels over time**

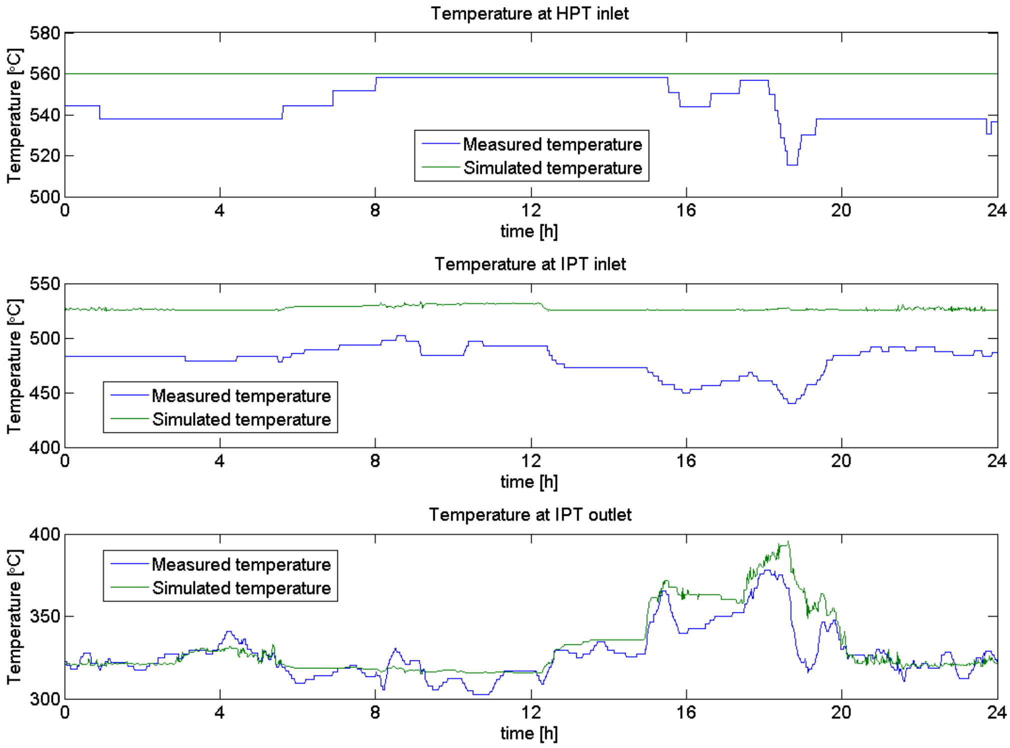

**Figure 4-7: Temperature levels over time**

The valve at the intermediate pressure turbine was always fully open during the time interval of interest and is not shown here.

## 4.3 Frequency Drop in a Real Case Scenario

On December 22, 2007, unit 3 of the nuclear power plant in Oskarshamn was tripped from the grid. This generator trip resulted in a loss of 1150 MW of production power which significantly affected the system frequency in the ENTSO-E RG Nordic grid; the system frequency dropped from 50.00 Hz to 49.58 Hz within 8 seconds. After some 60 seconds the system frequency was stabilized around 49.85 Hz.

In order to simulate this scenario, a very simplified power system with four generating units and one load was modeled. The power system is shown in figure 4-8.

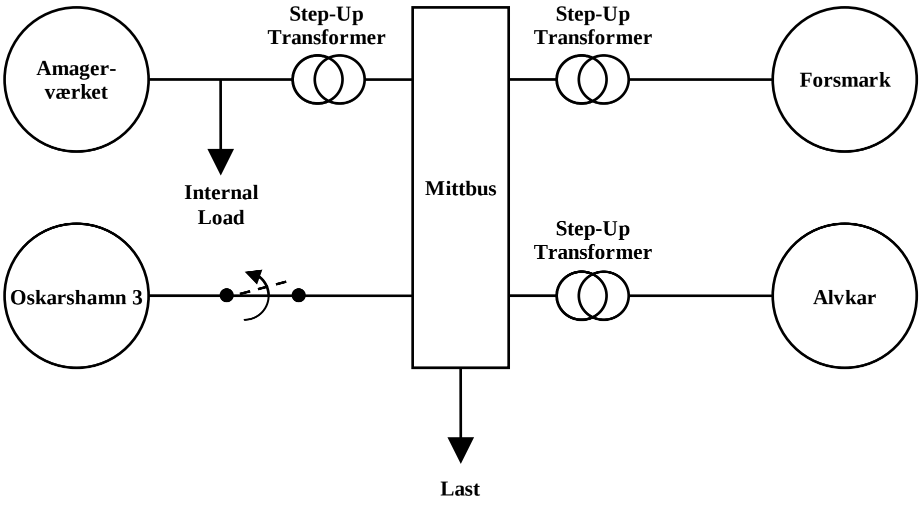

**Figure 4-8: Simplified ENTSO-E RG Nordic grid model**

All generators and the load are connected to fictional bus called Mittbus.

The fictional generator Forsmark accounts for the nuclear power stations and other power plants supplying base load. Forsmark is not equipped with any turbine governor system and, thus, holds its production constant throughout the entire simulation, independent of the frequency variation. An excitation system is provided to Forsmark giving it the ability to control the terminal voltage. The generator is connected to Mittbus via a step-up transformer.

The generator Alvkar combines all hydropower stations participating in frequency control. A fictional governor with electrical frequency as an input signal adjusts the power output. The generator supplies a part of the load prior to the fault and is expected to increase its power production after Oskarshamn 3 has been disconnected. The governor model used in Alvkar does not take into account the non-minimum phase property known from hydraulic turbines [9], but increases the power output immediately. Alvkar is connected to Mittbus via a step-up transformer and has also an excitation system installed.

Amagerværket is modeled with its internal consumption and step-up transformer. The generator is equipped with both a frequency controlling turbine governor and an excitation system. Amagerværket supplies load also before the disconnection of Oskarshamn 3.

The load Last accounts for all loads in the ENTSO-E RG Nordic system which is some 44 GW at the event. The model is both voltage and frequency dependent and accounts for both active and reactive power consumption.

The system base power is not equal to the generators' base power. Each generator has its own base power reference.

After 1 second, Oskarshamn 3 is disconnected. Figure 4-9 shows the simulated system frequency based on center of inertia plotted over time.

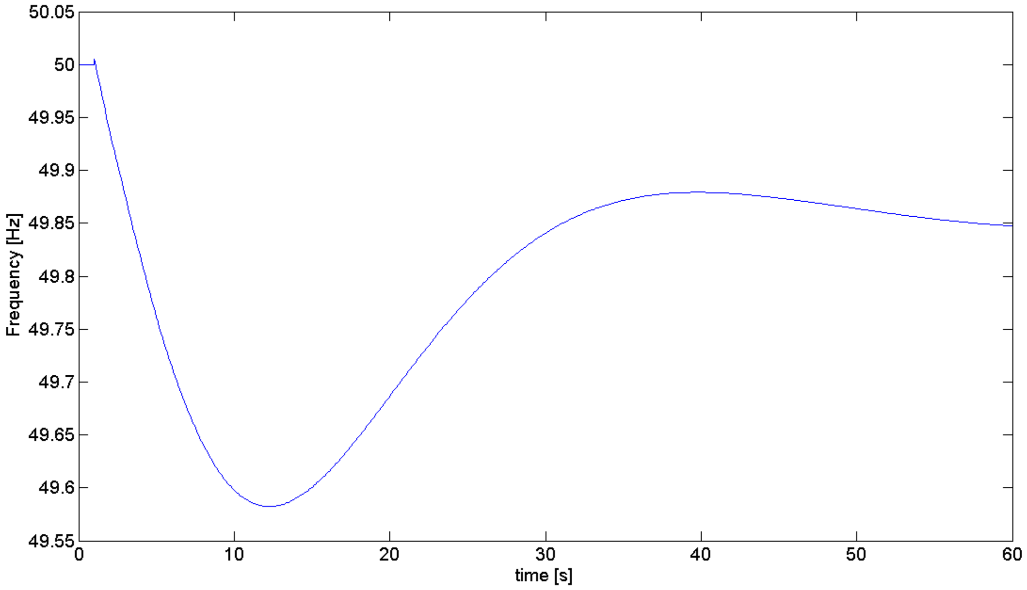

**Figure 4-9: Simulated system frequency following the disconnection of Oskarshamn 3**

As seen in figure 4-9, the system frequency decreases slower than during the real case scenario. The frequency minimum is reached after 11 seconds in the simulation compared to 8 seconds in the real case. This difference does, however, not influence the analysis here, since the aim is to see how Amagerværket reacts to such a system event.

The peak at the system frequency at 1 second is the result of numerical issues and does not have any physical relevance.

As shown in figure 4-10, after a slight overshot, the mechanical torque output settles at a new steady-state value. It should be observed that the torque is shown with respect to the generator's base power and not the base power of the system.

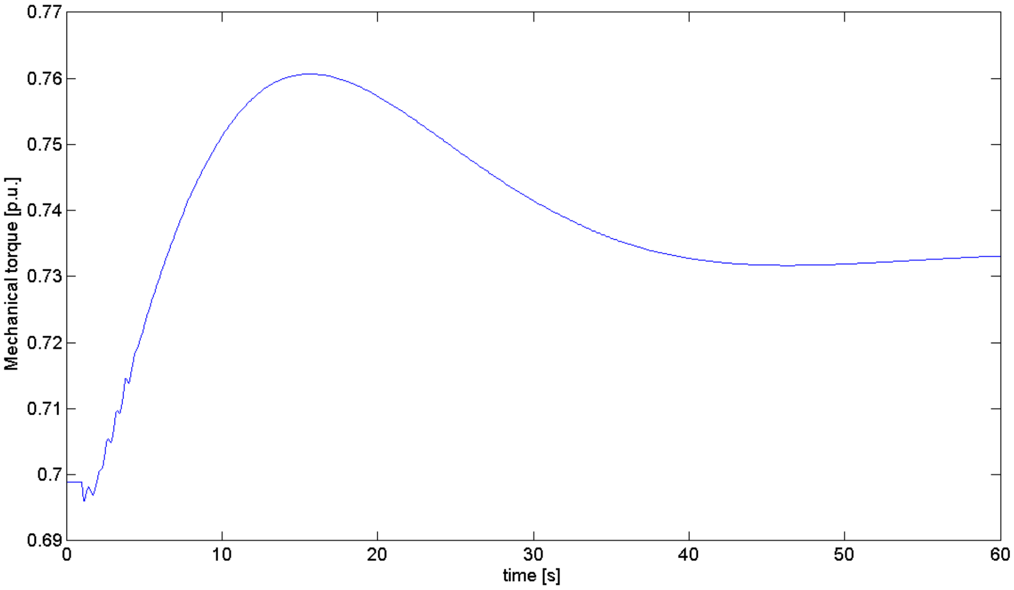

**Figure 4-10: Mechanical torque response at Amagerværket following the disconnection of Oskarshamn 3**

The curve showing the mechanical torque between 0.5 and 5 seconds is distorted due to numerical issues and does not have any physical relevance.

Figure 4-11 shows the valve positions of the high pressure turbine valve and the intermediate turbine pressure valve following the disconnection of Oskarshamn 3.

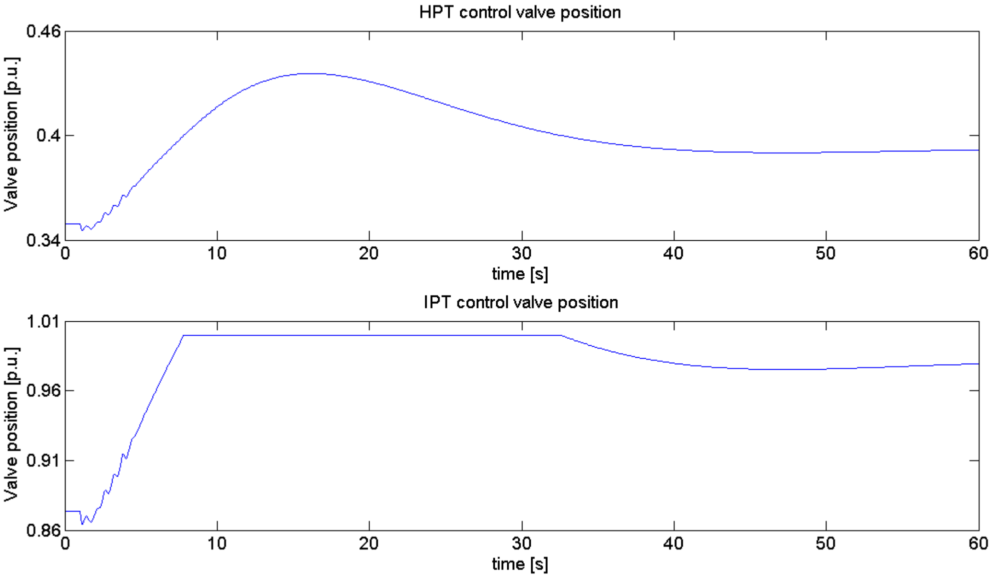

**Figure 4-11: Valve positions following the disconnection of Oskarshamn 3**

The valve positions of both high and intermediate pressure turbine increase almost linearly right after Oskarshamn 3 was tripped. This linear increase is due to the static in the frequency relevant part of the turbine governor, see figure 3-8. The position of the intermediate pressure turbine valve reaches its upper limit (100 %) and remains fully open for some 25 seconds.

For this event, no recordings for comparison are available. However, it is interesting to see how the plant behaves during a major event that can plausibly happen in the ENTSO-E RG Nordic system.

The curve showing the valve position between 0.5 and 5 seconds is distorted due to numerical issues and does not have any physical relevance.

# 5 Frequency Control in Denmark and Germany

## 5.1 Introduction

Both countries, Denmark and Germany, have been progressive in integrating renewable energy sources into their electricity production. Denmark covers a remarkable share of its electricity production with wind power, see figure 5-2. Germany has installed large capacities of both wind- and photovoltaic power, see figure 5-6.

In February 2011, the Danish government agreed on “Energy Strategy 2050”, a document drafting how Denmark could be become independent from coal, oil and gas by 2050. In particular, the document proclaims new wind farm projects, such as Kriegers Flak, that are going to double the Danish wind capacity of 2009 in 2020 [6].

Variations in wind speed cause fluctuations in generated power in wind turbines. These fluctuations in the Danish wind power generation require a solid, quickly responding and controllable energy source for providing stabilizing frequency control action. In Denmark, frequency control is to large extent achieved by importing balancing power, especially hydro power from Norway [4]. However, it is expected that Denmark’s neighboring countries are going to invest in wind and solar power as well and, therefore, require more balancing power for themselves. Hence, the competition on the market for balancing power is going to intensify and Denmark is advised to develop its own frequency control strategies [5].

Today, nuclear power covers about 20% of Germany’s electricity production. However, nuclear power is expected to decline within the next decade and, therefore, must be replaced by other sources. The Kyoto Protocol restricts the increase of $CO_2$ emissions caused by fossil-fuel fired power plants. Thus, the challenge towards a nuclear free and $CO_2$ low electricity production will force the integration of more renewable energy sources such as wind and solar power.

Electric infrastructure plays an important role when it comes to frequency control. Infrastructure and transmission capacity determines whether or not imports of balancing power are possible, and bottle necks occur. Bottle necks limit the possibilities of frequency control, in particular frequency restoring actions.

## 5.2 Denmark

### 5.2.1 Infrastructure

Denmark’s electricity grid is integrated in two, not synchronous grids: the ENTSO-E RG Continental European grid and the northern European ENTSO-E RG Nordic grid. The western part of Denmark (DK1), consisting of the peninsula Jutland (Danish: Jylland) and the island Fyn, is synchronous with the Continental European grid. The island Zealand (Danish: Sjælland) with the capital Copenhagen and other islands in Denmark’s eastern part (DK2) are synchronous with the Nordic grid. This division makes the situation in Denmark very special, in that it integrates two unsynchronized large transmission systems.

The responsible authority for the transmission network and for frequency control in Denmark, both for DK1 and DK2, is the Danish TSO Energinet.dk.

Denmark is well interconnected to its neighboring countries Germany, Norway and Sweden. An HVDC link between Fyn and Zealand – the Great Belt connection – has been in operation since 2010, connecting DK1 and DK2. Table 5-1 lists current interconnections to neighboring countries, and figure 5-1 shows the expected Danish transmission grid for 2030.

**Table 5-1: Denmark's interconnections to its neighboring countries and their respective capacities [27]**

| **From / To** | **Germany** | **Norway** | **Sweden** |
|---|---|---|---|
| **Denmark (DK1)** | 1500 MW (southbound)<br>950 MW (northbound), AC | 1040 MW, DC | 850 MW, DC |
| **Denmark (DK2)** | 600 MW, DC | - | 1900 MW, AC |

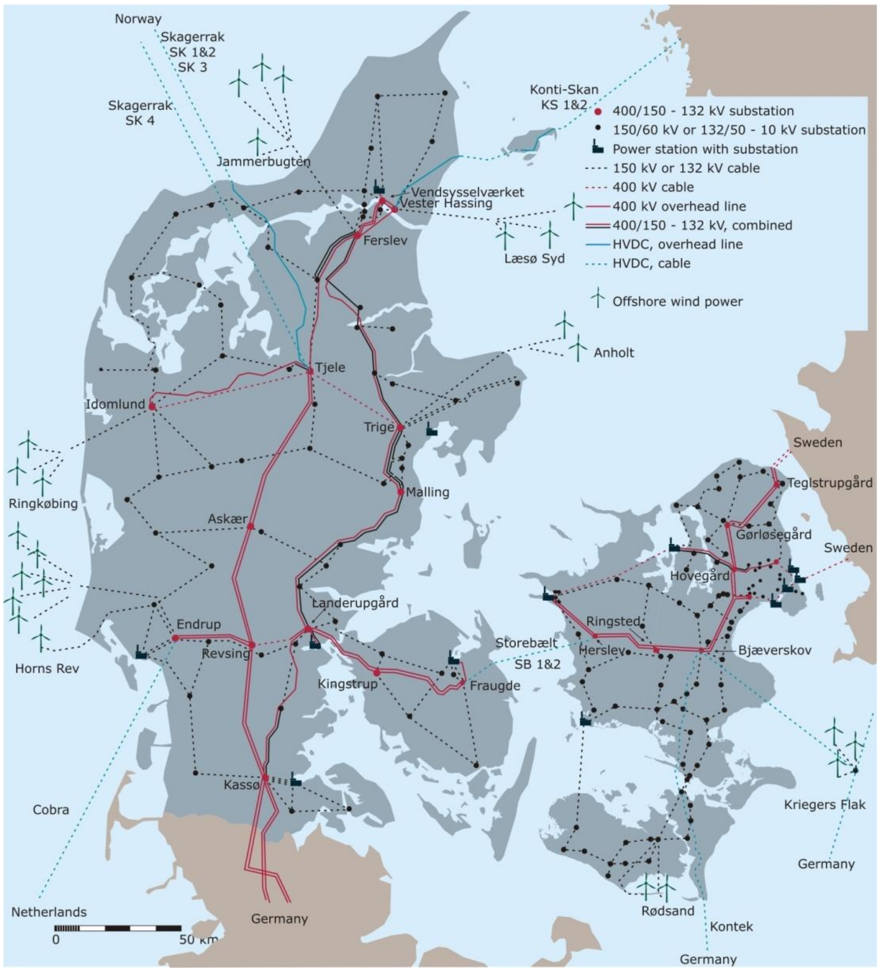

Figure 5-1: Expected Danish transmission grid in 2030 [27] (with permission from Energinet.dk)

In figure 5-1, a few transmission lines are not in place yet, e.g. Skagerrak 4 (SK4), Storebælt 2 (SB2) and Cobra (HVDC link connecting Denmark and the Netherlands).

In order to meet future power demands and for better integration of wind power, Denmark is investing in further transmission lines. New facilities are planned inside the country and to neighboring countries [27]. A few concrete projects are:

- The replacement of the existing 400 kV line between Tjele and Kassø on Jutland. The new transmission line will have a higher transport capacity and shall act as a backbone for Jutland's transmission grid. The increased capacity is going to be utilized when power is transferred through Jutland, and, additionally, is going to allow the safe integration of more wind power. The new transmission line is expected to start its operation sometime between 2012 and 2014.
- An additional DC submarine cable (SK 4) is going to increase the transmission capacity between Jutland and Skagerrak in Norway. The purpose of the additional link is the better integration of wind power and more competitiveness in electricity markets. Together with the project described above, this link will increase the transmission capacity from Norway to Germany using the Danish transmission grid as a transit corridor.
- The Dutch TSO Tennet and Energinet.dk are investigating the installation of a DC link between Jutland and the Netherlands (Name of the link: Cobra, see figure 5-1). This link is intended to increase grid stability and safe integration of renewable power generation in both countries. The underlying perception is that the wind patterns in the two countries are different [28]. Therefore, it is expected that Denmark and the Netherlands could partly compensate for each others' fluctuations in wind power generation. The anticipated capacity lies between 600 and 700 MW in both directions. Decommissioning is expected to take place in 2016 [28].

### 5.2.2 Electricity Production

From figure 5-2, it can be seen that a considerable share of Denmark's electricity production is covered by wind power. In 2009, a capacity of 3482 MW of wind power was installed in Denmark which generated 6.72 TWh of electric energy [29].

In February 2011, the Danish government put forward an energy policy proposal for the year 2050. By 2020, 30% of all electricity production should be covered by renewable energy sources. Furthermore, the installed wind power capacity should be increased to 6 GW [6]; that is twice the installed capacity from 2009.

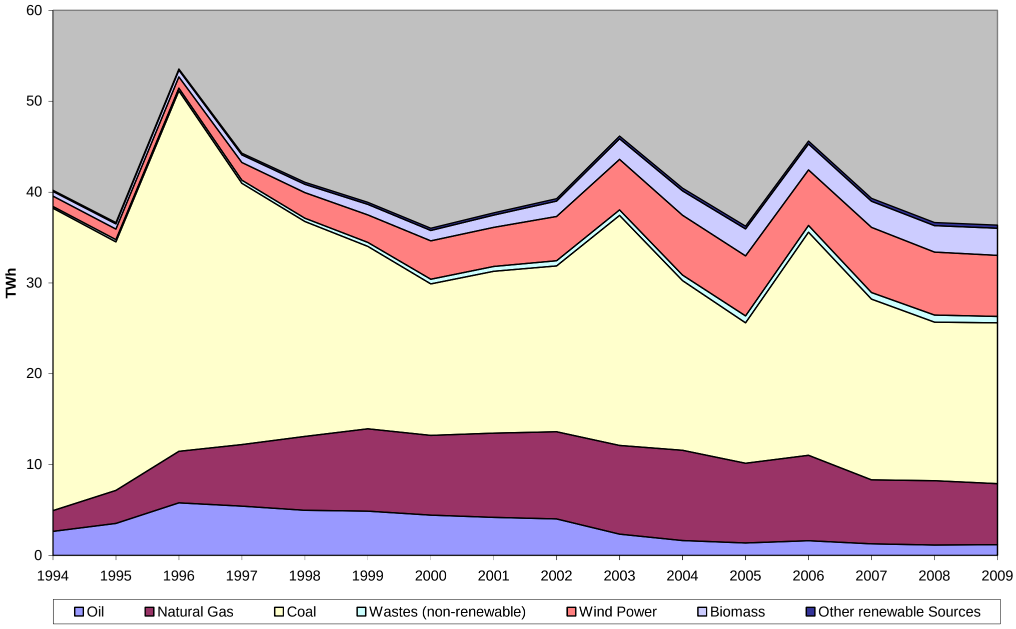

**Figure 5-2: Electricity production in Denmark per source and year from 1994 to 2009 [29]**

### 5.2.3 Frequency Control

The institution Energinet.dk is owned by the Danish state as represented by the Danish Ministry of Climate and Energy [27]. Frequency control is a set of ancillary services delivered by Energinet.dk. Reserves for frequency control are bought from power suppliers and power consumers from both Denmark and its neighboring countries.

The European continental and the Nordic grid, respectively, come with slightly different requirements regarding frequency control, see section 2.5. Therefore, a distinction is made between the western part of Denmark (DK1) and the eastern part of Denmark (DK2).

The following sections follow to a large extent [30] .

### 5.2.4 Frequency Control in DK1 (Jutland)

Frequency control in DK1 (Jutland) is divided into three categories:

- Primary reserves
- Secondary reserves, LFC (Load-frequency control)
- Manual reserves

### 5.2.5 Primary Reserves

Primary reserves are activated automatically as soon as the frequency deviates from its nominal value.

Each TSO within the ENTSO-E RG Continental Europe grid is responsible for sufficient primary reserves. Today, the total primary reserve requirement in the ENTSO-E RG Continental Europe area grid lies at ±3000 MW. The share that has to be covered by DK1 corresponds to the production in DK1 relative to the total production in the ENTSO-E RG Continental Europe system, and this share amounts to 27 MW for 2011.

#### 5.2.5.1 Technical Conditions

Primary reserves must be supplied linearly for frequency deviations between ±20 mHz and ±200 mHz relative to the nominal frequency. A dead-band of ±20 mHz is used throughout the entire ENTSO-E RG Continental Europe power system. This configuration is shown in figure 5-3.

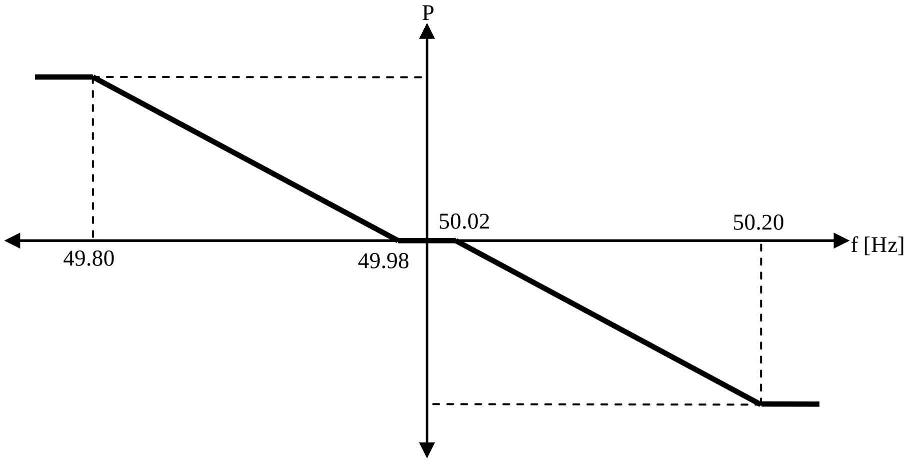

**Figure 5-3: Primary frequency control in the ENTSO-E RG Continental Europe power system with a dead-band of ±20 mHz**

The first half of all the reserves must be activated within 15 seconds; the total reserve within 30 seconds, i.e. with a dip in frequency down to 49.8 Hz, the Danish share of 27 MW must be fully activated within 30 seconds. The fully activated primary reserve must be maintained until secondary or manual reserves have taken over. However, primary reserves must be capable to be fully activated for a maximum of 15 minutes.

After primary reserves have been released through secondary reserves, primary reserves must be restored within 15 minutes.

Each participant in primary frequency control must be connected to Energinet.dk's Control Center via information technology in order to give Energinet.dk online access to certain measurements.

Energinet.dk does not send signals in order to activate the reserves. The activation of reserves relies on the supplier's own frequency measurements.

#### 5.2.5.2 Purchase of Primary Reserves

Primary reserve is purchased daily by Energinet.dk via a bidding process. Two different bidding processes for up- and down-regulating power are carried out.

The 24 hours period is divided into 6 blocks, each consisting of 4 hours. The bids must be submitted by 3 pm the day before, and the bids are binding on the bidder. Each bid must state an hour-by-hour volume and a price in DKK/MW. The minimum accepted volume is 0.3 MW.

The prices for up- and downward regulation, respectively, are set according to the highest bid accepted by Energinet.dk.

### 5.2.6 Secondary Reserves

In DK1, secondary reserve is commonly referred to as LFC (load-frequency control).

The secondary reserve serves two purposes: a) releasing priory activated primary reserves including restoring the nominal frequency and b) restoring any imbalances on interconnections to follow the agreed schedule. Secondary reserves are centrally activated by Energinet.dk.

The ENTSO-E RG Continental Europe recommendation lies at ±90 MW, but it is up to the TSO to increase reserved power for secondary control. Energinet.dk's requirements on secondary reserve are based on ENTSO-E RG Continental Europe's recommendations. Energinet.dk has to ensure that uncertainties of wind forecasts are taken into account. The TSO is allowed to purchase up to one third of the secondary reserve outside DK1, given that the available transmission capacity is large enough.

#### 5.2.6.1 Technical Conditions

Secondary control must be fully activated within 15 minutes and must be able to remain activated continuously.

Energinet.dk sends a signal to each participating unit in the case secondary control needs to be activated.

Each participant in secondary control must be connected to Energinet.dk via information technology infrastructure. This connection allows Energinet.dk measuring data online.

#### 5.2.6.2 Purchase of Secondary Reserves

Energinet.dk purchases secondary reserve power on a monthly basis following a bidding process. The respective requirements for the following month are posted on Energinet.dk's website latest by the 10th of each month.

Only symmetrical bids are allowed, i.e. bids with equal capacity for up- and down-regulation power.

Bids are accepted following an evaluation of the received bids. The evaluation takes into account the following:

- Price of service
- Place of delivery
- Technical properties of the production and consumption unit

Energinet.dk freely accepts bids and may ask for bid changes. The price is not the only underlying asset for an accepted bid, and the price is negotiated individually between Energinet.dk and the supplier.

If a supplier is not able to deliver the agreed secondary reserve, the supplier is required to inform Energinet.dk about when the reserve can be re-established.

The prices for up-regulation power are settled per MWh at the DK1 electricity spot price plus 100 DKK/MWh. This price lies at least as high at the power price for up-regulation.

The prices for down-regulation power are settled per MWh at the DK1 electricity spot price minus 100 DKK/MWh. This price does not exceed the power price for down regulation.

The energy supply is calculated by Energinet.dk.

### 5.2.7 Frequency Control in DK2 (Zealand)

Services regarding frequency control in DK2 consist of:

- Frequency-controlled normal operation reserves (FNR)
- Frequency-controlled disturbance reserves (FDR)
- Manual reserves

### 5.2.8 Frequency-Controlled Normal Operation Reserves (FNR)

Frequency-controlled normal operation reserve is activated automatically in response to a frequency deviation.

In the ENTSO-E RG Nordic grid, the combined requirement for frequency-controlled normal operation reserve sums up to 600 MW. The share that needs to be covered by Energinet.dk is based on the production in DK2 relative to the total production in the ENTSO-E RG Nordic system. This share is determined annually and was set to be 23 MW in 2011.

The rules in ENTSO-E RG Nordic allow import and export of frequency-controlled normal operation reserves. However, a minimum of two thirds must be supplied within the TSO’s own area.

#### 5.2.8.1 Technical Conditions

The operation reserve must be supplied linearly up to a frequency deviation of ±100 mHz relative to the nominal frequency. Deliveries must be made without a dead-band, see [30].

The reserve must be supplied linearly for frequency deviations from 0 to 100 mHz and must be fully active after a maximum of 150 seconds, regardless of the magnitude of frequency deviation, i.e. with a dip in frequency down to 49.90 Hz, the Danish share of 23 MW must be fully activated. Figure 5-4 shows the supply of FNR with respect to frequency.

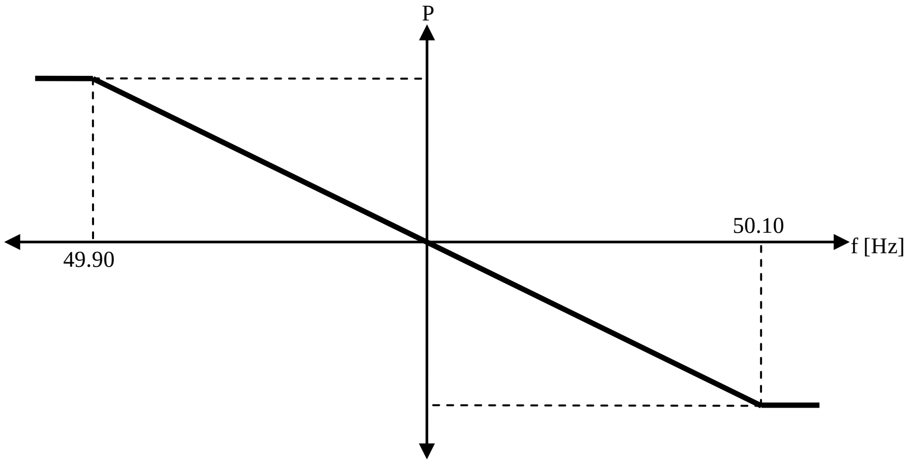

**Figure 5-4: Supply of FNR in the ENTSO-E RG Nordic power system without any dead-band**

The supplier must guarantee continuous regulation.

Each supplier of frequency-controlled normal operation reserve must be connected to Energinet.dk via information technology infrastructure.

#### 5.2.8.2 Purchase of Frequency-Controlled Normal Operation Reserves

Energinet.dk buys two different kinds of frequency-controlled normal operation reserve: a) upward regulation power and b) downward regulation power. The purchase is done via auctioning and is carried out once every day.

A 24 hour period is divided into 6 blocks, each consisting of 4 hours. The bids must be submitted by 3 pm the day before, and the bids are binding on the bidder. Each bid must state an hour-by-hour volume and a price in DKK/MW. The minimum accepted volume is 0.3 MW. Bids are either accepted in their entirety or not at all.

The prices for up- and downward regulation are set according to the highest bid accepted by Energinet.dk.

### 5.2.9 Frequency-Controlled Disturbance Reserves (FDR)

Frequency-controlled disturbance reserve is intended to compensate for outages of major generation units or transmission lines. The reserve constitutes of upward regulation only and is activated automatically after sudden frequency drops under 49.90 Hz. The reserve must remain active until the balance has been restored or until the manual reserves have taken over.

The combined requirement in the ENTSO-E RG Nordic grid is determined by the capacity of the largest nuclear power station minus 200 MW. The total requirement is then split proportionally to the dimensioning faults of each individual area. Energinet.dk’s share is determined by the largest dimensioning fault in Eastern Denmark (DK2) and is fixed each Thursday for the coming week.

Energinet.dk purchases FDR via an auctioning process which is held daily. For 2011, the approximate share to be covered by Energinet.dk is 150 MW.
Import and export of frequency-controlled disturbance reserve is allowed. However, at least two thirds of the reserves must be supplied within the respective area.

### 5.2.9.1 Technical conditions

Frequency-controlled disturbance reserve must be able to: a) supply inverse-linear power at a frequency range between 49.90 and 49.50 Hz, b) supply 50% of the response within 5 seconds and c) supply the remaining 50% of the response within an additional 25 seconds. Figure 5-5 shows the inverse electrical power supply between 49.50 and 49.90 Hz.

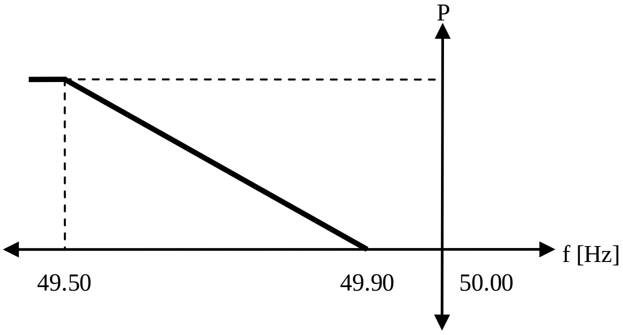

**Figure 5-5: Inverse power supply between 49.50 and 49.90 Hz**

Each participating unit must be connected to Energinet.dk via information technology infrastructure.

Energinet.dk does not activate the reserve; instead, the participating unit’s frequency measurement must respond accordingly.

### 5.2.9.2 Purchase of Frequency-Controlled Disturbance Reserves

Energinet.dk buys frequency-controlled disturbance reserve as upward regulation. A 24 hours period is divided into 6 blocks of 4 hours each. The bids for the following day must be sent to Energinet.dk by 3 pm the forgoing afternoon. The submitted bids are binding to the bidder.

Each bid must be for a minimum of 0.3 MW, and the price must be given in DKK/MW.

Energinet.dk sorts the received bids according to their price per MW. The final price is then set by the most expensive bid accepted. Bids are accepted entirely or not at all.

The delivered energy volume supplied is not calculated.

### 5.2.10 Manual Reserves in DK1 and DK2

Manual reserve is a manual upward and downward regulation reserve. The reserve is used to release previously activated LFC (DK1) and FNR/FDR (DK2), respectively. Manual reserve is activated from Energinet.dk's control center.

#### 5.2.10.1Technical conditions

The reserve must be able to be fully activated after 15 minutes.

The supplier must be connected to Energinet.dk via information technology infrastructure.

#### 5.2.10.2Purchase of Manual Reserves

Energinet.dk purchases manual reserves on daily auctions for each single hour. Two separate auctions are held: a) one for upward regulation and b) one for downward regulation.

The required reserve for the upcoming day is announced on Energinet.dk's homepage at 9 am. The suppliers' bids must be submitted by 9:30 am, they must be stated in MW and their price must be given in DKK/MW. The minimum bid size allowed is 10 MW and the maximum bid size is 50 MW. All bids made until 9:30 am are binding to the bidder.

The received bids are sorted by Energinet.dk according to their prices per MW. Bids are accepted entirely or not at all.

The price for the payment for all accepted bids is set by the highest price for upward and downward regulation, respectively.

Supplied energy volumes are calculated based on the regulation power market [31].

## 5.3 Germany

### 5.3.1 Infrastructure

Germany's power system is synchronous with the ENTSO-E RG Continental European grid. The power system is strongly interconnected to its neighboring countries, and the domestic grid is quite densely meshed. In order to increase system stability and generation from renewable sources, a number of additional interconnections are planned, both inside Germany and to its neighboring countries. The UCTE Development plan from 2009 suggests new transmission lines to Belgium, France, the Netherlands and Luxemburg [32].

### 5.3.2 Electricity production

In 2010, the total electrical energy production in Germany amounted to 620.8 TWh. In the same year, Germany had a capacity of 27 GW wind power installed which generated 37.5 TWh of electricity [33]. Figure 5-6 shows the electricity production in Germany per source and year from 1990 to 2010.

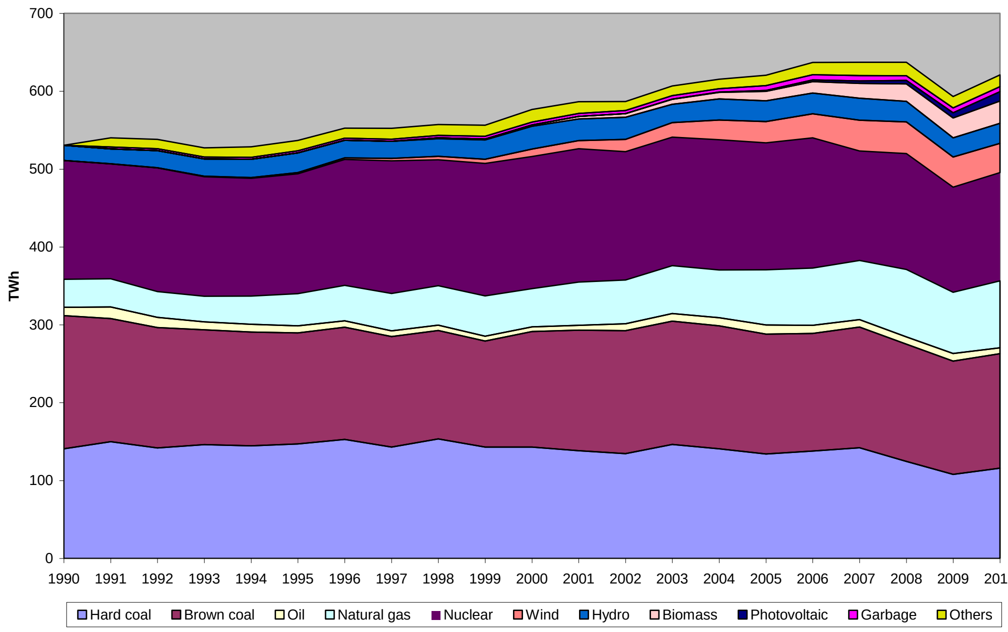

**Figure 5-6: Electricity production in Germany per source and year from 1990 to 2010 [33]**

The figures below show the distribution of wind (see figure 5-7 and figure 5-8) and solar power (see figure 5-9 and figure 5-10) capacity state by state. The data illustrated contains only capacities installed according to the Erneuerbare Energien Gesetz (EEG)[4] by the 31st of December 2009.

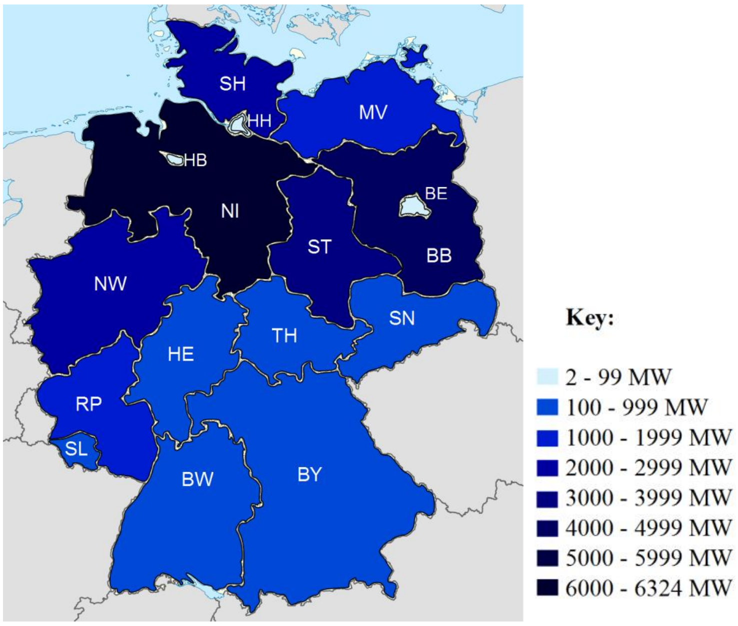

**Figure 5-7: Installed wind power capacity per state according to EEG by 2009-12-31 [34]**

---

[4] Erneuerbare-Energien Gesetz (EEG) is a set of rules and regulations that entitles to financial subsidies for generated power by renewable energy sources, e.g. wind and solar power. A fixed feed in tariff is guaranteed for a period up to 20 years.

From figure 5-7, it can be seen that the installed capacity in wind power is mainly concentrated in the northern parts of Germany.

Figure 5-8 shows the installed capacity of wind power per state in MW.

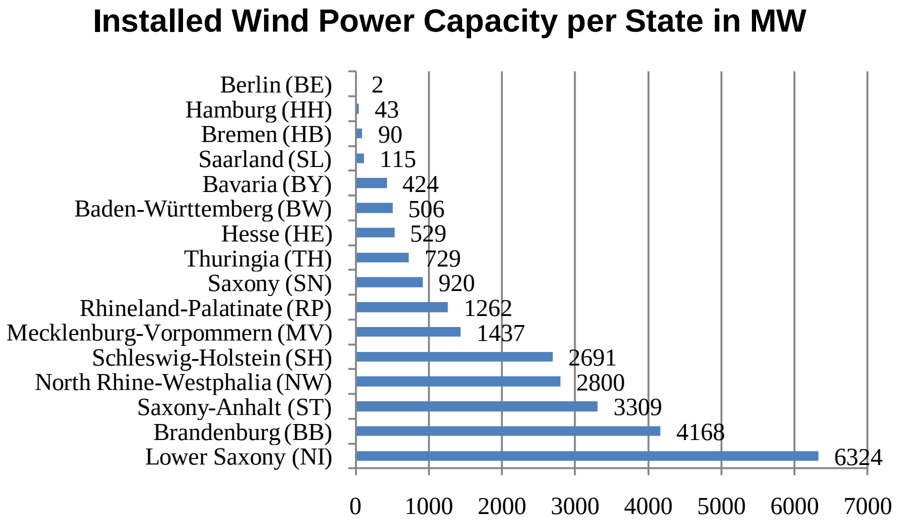

**Figure 5-8: Installed wind power capacity per state according to EEG by 2009-12-31 [34]**

In addition to wind power, a considerable amount of photovoltaic generation is installed in Germany. By the end of 2010, a total capacity of 17 GW of photovoltaic capacity was installed [35].

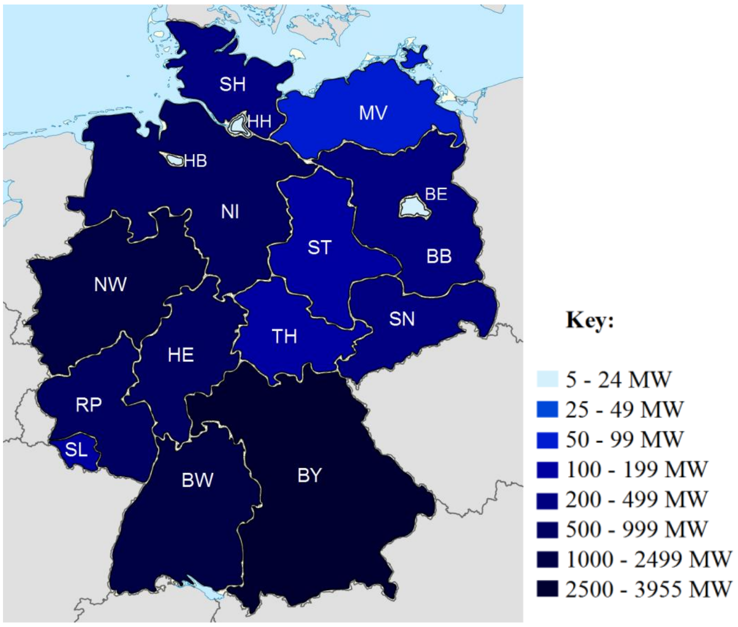

**Figure 5-9: Installed solar power capacity per state according to EEG by 2009-12-31 [34]**

From figure 5-9, it can be seen that the installed capacity in solar power is concentrated in the southern and western parts of Germany.

Figure 5-10 shows the installed capacity of solar power per state in MW.

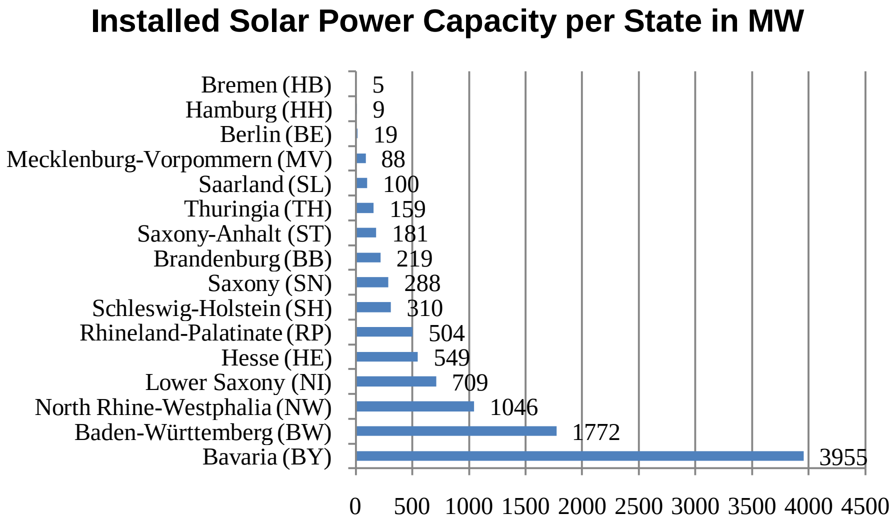

**Figure 5-10: Installed solar power capacity per state according to EEG by 2009-12-31 [34]**

### 5.3.3 Frequency Control

Figure 5-11 indicates the balancing areas in Germany.

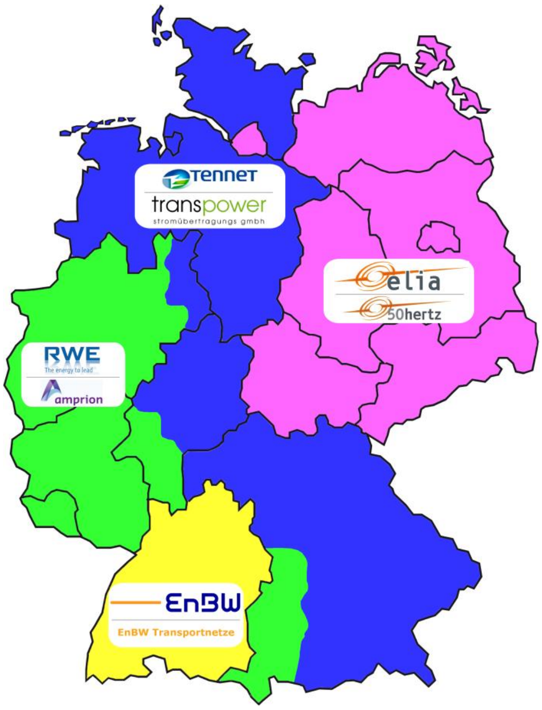

**Figure 5-11: The balancing areas of the four German TSOs [36]**

Germany represents one control block which is divided into four balancing (or control) areas[5], and, consequently, Germany has four TSOs. Tennet, a Dutch TSO, owns the German transmission grid in the north-west, middle and south-east (see the blue area in figure 5-11). 50 Hertz Transmission is responsible for the north-eastern and eastern part of Germany and is to 60% owned by the Belgian TSO Elia (see the purple area in figure 5-11). The western part is owned by Amprion, a subsidiary of RWE (see the green area in figure 5-11). The transmission grid in the south-western part, meaning the state Baden-Württemberg, is owned by EnBW Transportnetze AG (Energie Baden-Württemberg) (see the yellow area in figure 5-11).

### 5.3.4 Market for Control Reserves

Since 2001, the German TSOs purchase primary-, secondary- and minute reserves on a transparent and open market. The purchase is carried out via a tendering procedure where both electricity suppliers and consumers can participate. A necessary precondition for participation in the tendering procedure is a framework agreement with the respective TSO. Bids for all kinds of control reserves cannot be submitted without such a framework agreement.

Since December 1st 2006, all four TSOs buy minute reserves via a common webpage www.regelleistung.net. The purchase of primary and secondary reserves was started to be carried out through the same common webpage a year later, on December 1st 2007 [37].

### 5.3.5 Primary Control

The purpose of primary control is to keep the balance between generation and consumption in a synchronous power system. Primary control reserves are activated within a few seconds after a frequency deviation and are jointly provided by all TSOs in the entire ENTSO-E RG Continental Europe grid [13]. Primary control stabilizes the system frequency, but does not restore the frequency’s nominal value.

Each TSO within the ENTSO-E RG Continental Europe grid is responsible for sufficient primary control reserves. Today, the total primary control reserve requirement in the ENTSO-E RG grid lies at ± 3000 MW. The share that has to be covered by Germany corresponds to the production in Germany relative to the total production in the ENTSO-E RG system, and this share amounts to 612 MW for 2011.

The minimum network power frequency characteristic of primary control in the UCTE area is set to be 15000 MW/Hz. The average network power frequency characteristic is 30% higher and amounts to 19500 MW/Hz.

#### 5.3.5.1 Technical Conditions

The technical conditions for primary control in Germany follow largely [13].

The reserve must be supplied linearly for a frequency deviation between ±20 mHz and ±200 mHz, i.e. a dead-band of ±20 mHz is permitted. Primary regulation reserves must be fully activated at a frequency deviation of ±200 mHz, see figure 5-3. The first half of the reserve must be activated within 15 seconds; the total reserve within 30

---

[5] In German: Regelzonen

seconds, i.e. with a dip in frequency down to 49.8 Hz, the German share of 612 MW must be fully activated within 30 seconds. Primary reserves must be delivered until secondary or manual reserves can take over. However, a minimum time span of 15 minutes, during which primary control must be supplied, is required.

Once primary control reserve is released through secondary control, the primary control reserve must be restored within 15 minutes.

Each control area is entitled to increase primary control reserve by up to 90 MW in order to compensate for the obligations of other control areas.

#### 5.3.5.2 Purchase of Primary Reserves

All four German TSOs purchase primary reserves via their common webpage www.regelleistung.net. Auctions are held monthly, usually on the Tuesday closest to the 15th of each month, for the following month. The required reserve is published on the webpage well before the date of auctioning.

No separate auctions for positive and negative reserves are held.

### 5.3.6 Secondary Control

In Germany, load-frequency control (LFC) is used for secondary control. LFC is controlled centrally by the respective TSO.

Secondary control serves two purposes: a) to release primary control reserves and b) to restore the nominal frequency and scheduled power flows on interconnecting transmission lines. The TSO responsible for a specific control area is in charge of activating secondary control reserves when necessary. Thereby, the active power set points in participating units are adjusted in order to increase or decrease the active power output.

#### 5.3.6.1 Technical Conditions

The technical conditions for secondary control in Germany follow largely [13].

Secondary control must be fully activated within 15 minutes and must be able to remain activated continuously.

A unit participating in secondary control must be connected to the respective TSO's load-frequency controller through information technology infrastructure.

#### 5.3.6.2 Purchase of Secondary Reserves

All four German TSOs purchase secondary reserves via their common webpage www.regelleistung.net. Auctions are held monthly, usually on Thursdays (two days after the auction for primary control reserves), for the following month. The required reserve is published on the webpage well before the date of auctioning.

### 5.3.7 Minute Reserves

The objective of minute reserves is to release secondary reserves in balances system situations. Additionally, minute reserves can be used to restore the nominal system frequency after major incidents, and, therewith, release activated primary reserves. The respective TSO is responsible for activating minute reserves when necessary.

#### 5.3.7.1 Purchase of Minute Reserves

All four German TSOs purchase minute reserves via their common webpage www.regelleistung.net. Auctions are held daily for the following day. The required reserve is published on the webpage well in advance.

The selection of bids is based on the demanded capacity fee of the bidder. However, the actual activation of minute reserves is based on the energy prices specified by the bidder. Currently, each TSO has his own merit-order[6] list, but work is in progress to implement a common merit-order list for all TSOs.

---

[6] In Swedish: Utbud/efterfrågan

# 6 Conclusions

## 6.1 Conclusions on Modeling and Simulations

A thermal power plant with its relevant components was modeled in this project. The model combines electrical, mechanical and thermodynamic components in one overall model. Hence, it was possible to include three engineering domains into one single model.

Object-orientated modeling was found to be suitable for a multi-domain model. Similar models could quickly be adapted to their final purpose. The utilization of connectors allowed connecting sub-model with just one equation. Since acausal modeling was used, there was no need to derive an overall, state space based equation system. Such equation systems are usually required for integrating simulation programs.

The model was assembled with components from the Modelica standard library and two additional Modelica libraries. The usage of all three libraries was found to be convenient.

The valve positioning via the turbine governor allows following a defined or time-varying power set point (see figure 4-2 and figure 4-3). In addition, the turbine governor is able to appropriately respond to frequency deviations (see figure 4-10). Consequently, primary frequency control action in a thermal power plant can be simulated with the derived model.

## 6.2 Conclusions on Frequency Control in Denmark and Germany

In the ENTSO-E RG Continental Europe and ENTSO-E RG Nordic power systems, different strategies and rules regarding frequency control are applied. The different frequency control actions set in Denmark and Germany are listed in table 6-1.

**Table 6-1: Frequency Control Actions in Denmark and Germany**

| Region / Country | Frequency Control Actions |
|---|---|
| **DK1 (Jutland)** | • Primary reserves<br>• Secondary reserves (with Load-frequency control (LFC))<br>• Manual reserves |
| **DK2 (Zealand)** | • Frequency-controlled normal reserve (FNR)<br>• Frequency-controlled disturbance reserve (FDR)<br>• Manual reserves |
| **Germany** | • Primary reserves<br>• Secondary reserves (with Load-frequency control (LFC))<br>• Tertiary reserves |

In both DK1 (Jutland) and Germany, Load-Frequency control (LFC) is used for the realization of secondary frequency control. LFC is controlled centrally by the respective TSO.

The possibilities for delivering reserves for frequency control are not limited to the balancing area connected. The rules in both systems, ENTSO-E RG Continental Europe and Nordic, allow the import and export of frequency control reserve. This possibility does, however, prerequisite free capacities on transmission lines.

Primary control reserves must be supplied up to 15 minutes. In contrary, FNR and FDR must be supplied continuously until they are released by means of manual reserves. There is no requirement on how fast manual reserves must be activated and it is up to the TSO when manual reserves are put in action.

Many other countries in Europe can be expected to follow the trend to install more and more wind power. Especially Denmark’s neighboring countries Germany, Sweden and the Netherlands have proposed scenarios indicating a considerable increase in installed wind power capacity. Then the question rises, will Denmark and Germany be able to rely on their neighbor’s help when it comes to balancing power? A possible future scenario includes increasing prices and an intensifying market for balancing power. The market for balancing power may become more profitable for electricity supply companies. Fast responding units may be of higher financial value than power plants with high (fixed) generation capacity.

## 6.3 Future Work

Possible extensions of the thermal model are the integration of bypass valves, pumps, relevant pipes and fluid storage in order to improve the steam cycle. In particular, the bypass valves may contribute to a more complete picture of the steam facilities. A model of the condenser or district heating system could be added. Eventually, the entire, closed steam cycle with its ancillary control loops could be modeled.

The control valves could be modeled more in detail. This addition would include servo motors for gate opening and closing as well as the overall valve characteristics.

Secondary control could be implemented by an additional input signal to the turbine governor. This feature would allow simulating how the frequency is restored once it has deviated and primary frequency control has been activated.

The implementation of negative- and zero-sequence components could be interesting for the study of non-symmetrical electrical operation.

The power plant’s internal consumption could be modeled in more detail. Due to the utilization of pumps and other facilities driven by electrical motors, the load can be expected to be both frequency and voltage dependent.

The implementation of control reference curves for different fuels would allow studies on the usage of different fuels. The heat content of fossil fuels is generally higher than of biomass.

# 7 List of Figures

# 8 Bibliography

[1] Sven Erik Mattsson, Hilding Elmqvist, and Martin Otter, "Physical system modeling with Modelica," , vol. 6, 1998, pp. 501-510.
[2] M Cregan and D Flynn, "Advances in Power Plant Technology," in *Thermal Power Plant Simulation and Control*. London: Institution of Electrical Engineers, 2003.
[3] Peter Fritzson, *Principles of Object-Oriented Modeling and Simulation with Modelica 2.1*.: Wiley-IEEE Press, 2004.
[4] Reinhard Kaisinger, "Meeting Protocol: Meeting at Amagerværket on 02-22-2011," Vattenfall Research and Development AB, Stockholm, Internal Report 2011.
[5] Teknologisk Institut, "EcoGrid.dk Phase I - Summary Report," 2007.
[6] The Danish Ministry of Climate and Energy, "Energy Etrategy 2050 - From Coal, Oil and Gas to Green Energy," February 2011. www.kemin.dk
[7] wikipedia.org. Thermal power station. 2007. http://en.wikipedia.org/wiki/Thermal_power_station
[8] Reinhard Kaisinger, "Meeting Protocol: Meeting at Amagerværket 2011-05-03 - 2011-05-04," Vattenfall Research and Development AB, Copenhagen, Internal Report 2011.
[9] Prabha Kundur, *Power system stability and control*. New York: McGraw-Hill, 1994.
[10] Alberto Leva and C Maffezzoni, "Modelling of Power Plants," in *Thermal Power Plant Simulation and Control*. London: Institution of Electrical Engineers, 2003.
[11] Jan Machowski, *Power system dynamics: stability and control*. Chichester: Wiley, 2008.
[12] Vattenfall A/S, "Amager Power Station," 2007.
[13] UCTE, "P1 – Policy 1: Load-Frequency Control and Performance [C]," 2009.
[14] Modelica Association. Modelica Libraries. 2011. https://www.modelica.org/libraries
[15] Modelica Association, "Modelica - A Unified Object-Oriented Language for Physical Systems Modeling: Language Specification, Version 3.1," 2009.
[16] Peter Fritzson and Vadim Engelson, "Modelica - A Unified Object-Oriented Language for System Modeling and Simulation," Linköping, 1998.
[17] Systemes Dassault, "Dymola Manual Part 1," Manual 2010.
[18] Mats Larsson, "ObjectStab - An educational tool for power system stability studies," vol. 19, no. 1, pp. 56 - 63, 2004.
[19] Francesco Casella and Alberto Leva, "Object-Oriented Modelling & Simulation of Power Plants with Modelica," , Milano, 2005.
[20] Francesco Casella and Alberto Leva, "Modelica Open Library for Power Plant Simulation: Design and Experimental Validation," , Linköping, 2003, pp. 41-50.
[21] Modelica Association. Modelica License Version 2. 2008. https://www.modelica.org/licenses/ModelicaLicense2#The_Modelica_License_2-outline
[22] Francesco Casella. The ThermoPower library Home Page. 2009. http://home.dei.polimi.it/casella/thermopower/
[23] ABB, "Calculation Settings Amager Power Station, Denmark," Internal Data 2009.
[24] D H Cooke, "On prediction of off-design multistage turbine pressures by Stodola's Ellipse," vol. 107, no. 3, pp. 596-606, 1985.

[25] "Documentation on the Steam Cycle at Amagerværket with Steam Reference Values," Internal Data 2005.

[26] Amagerværket Energi E2, "Documentation on the Control System at Amagerværket," Copenhagen, Internal Data 2010.

[27] Energinet.dk. Energinet.dk. http://www.energinet.dk/EN/Sider/default.aspx

[28] Energinet.dk. Cable to the Netherlands - COBRAcable. 2011. http://www.energinet.dk/EN/ANLAEG-OG-PROJEKTER/Infrastructure-projects-electricity/Cable-to-the-Netherlands-COBRA/Sider/Cable-to-the-Netherlands-COBRA.aspx

[29] Danish Energy Agency, "Energy Statistics 2009," 2010.

[30] Energinet.dk, "Ancillary services to be delivered in Denmark: Tender conditions," 2010.

[31] Energinet.dk, "Regulation C2: The balancing market and balance settlement, Rev. 2," 2008.

[32] UCTE, "UCTE Transmission Development Plan," 2009.

[33] Bundesministerium für Wirtschaft und Technologie. Zahlen und Fakten Energiedaten: Nationale und Internationale Entwicklung (in German). Excel File. 2011.

[34] Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen "EEG-Statistikbericht 2009 (in German)," 2011.

[35] Naturschutz und Reaktorsicherheit Bundesministeriums für Umwelt. 2011 Erneuerbare Energien 2010 (in German). Excel File.

[36] wikipedia.org. Regelleistung (in German). 2010. http://de.wikipedia.org/wiki/Regelleistung_%28Energie%29

[37] 50Hertz Transmission GmbH, Amprion GmbH, EnBW Transportnetze AG, and TenneT TSO GmbH. regelleistung.net - Internetplattform zur Vergabe von Regelleistung. https://www.regelleistung.net/regelleistungWeb/?language=en

# Appendix A  Models in Dymola

The models derived in Dymola are illustrated and their functioning is described.

In general, in single input-single output models, inputs are named *u* and outputs *y*.

Typically, model blocks in Dymola show two strings. The title of the block is usually given above the block. One major parameter is shown either in or below the block. However, sometimes the title is shown in or below the block when no parameter is shown.

In accordance with Dymola, Latin characters are used instead of Greek characters, e.g. ω is written as *w*.

## A.1. Automatic Voltage Regulator

Figure A-1 shows the automatic voltage regulator model.

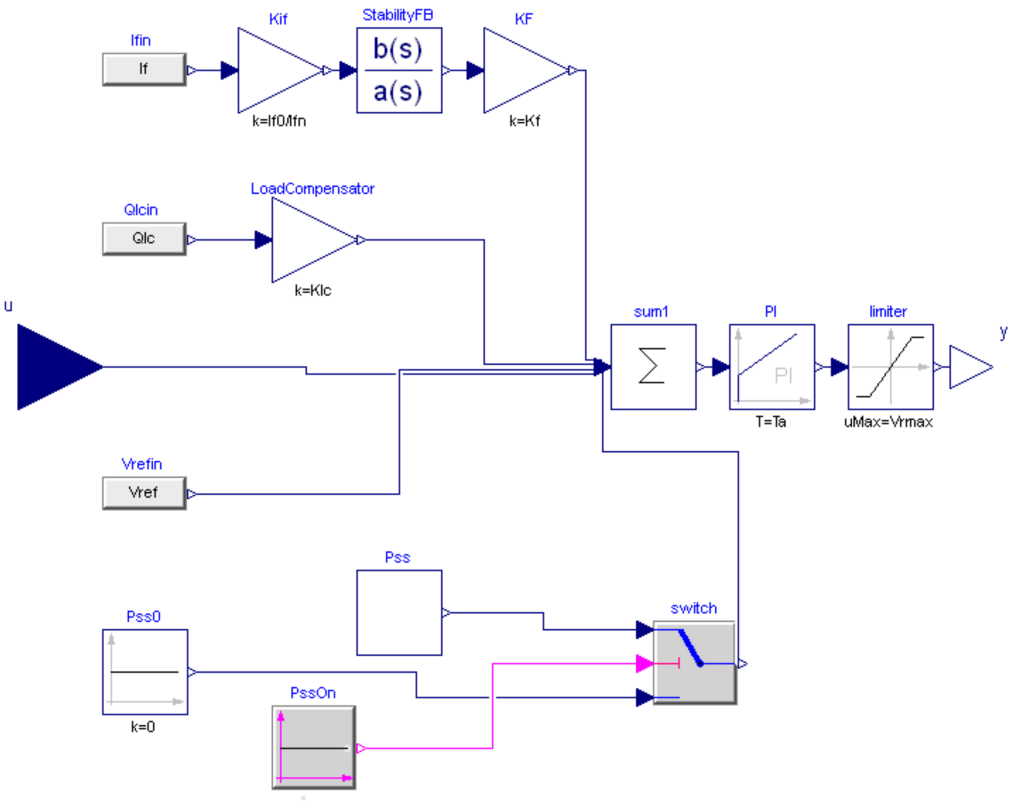

**Figure A-1: Automatic voltage regulator**

The block *sum1* is the central summarization block where all signals affecting the field voltage are summed.

The block *Ifin* acts as an input for the field current in the rotor *If*. The current is scaled by the ratio of its no-load reference value *If0* over its nominal load reference value *Ifn*.

Then the signals is subjected to the input filter *StabilityFB* and amplified by the gain *KF*.

*Qlcin* is a parameter accounting for load compensation which is amplified by *LoadCompensator*.

The input *u* is the instant generator output voltage.

*Vrefin* with its parameter *Vref* is the reference value for the generator output voltage.

The Boolean logic together with the block *Pss* allows choosing whether the PSS is enabled or disabled. When the Boolean variable *Psson* is '*one'* or '*true'*, the PSS is active, otherwise it is disabled.

After the summation of all input signals, the result is fed into the PI controller *PI*. *Limiter* subjects the PI controller's output to its respective upper and lower limits.

## A.2. Power System Stabilizer

Figure A-2 shows the model of the power system stabilizer (PSS).

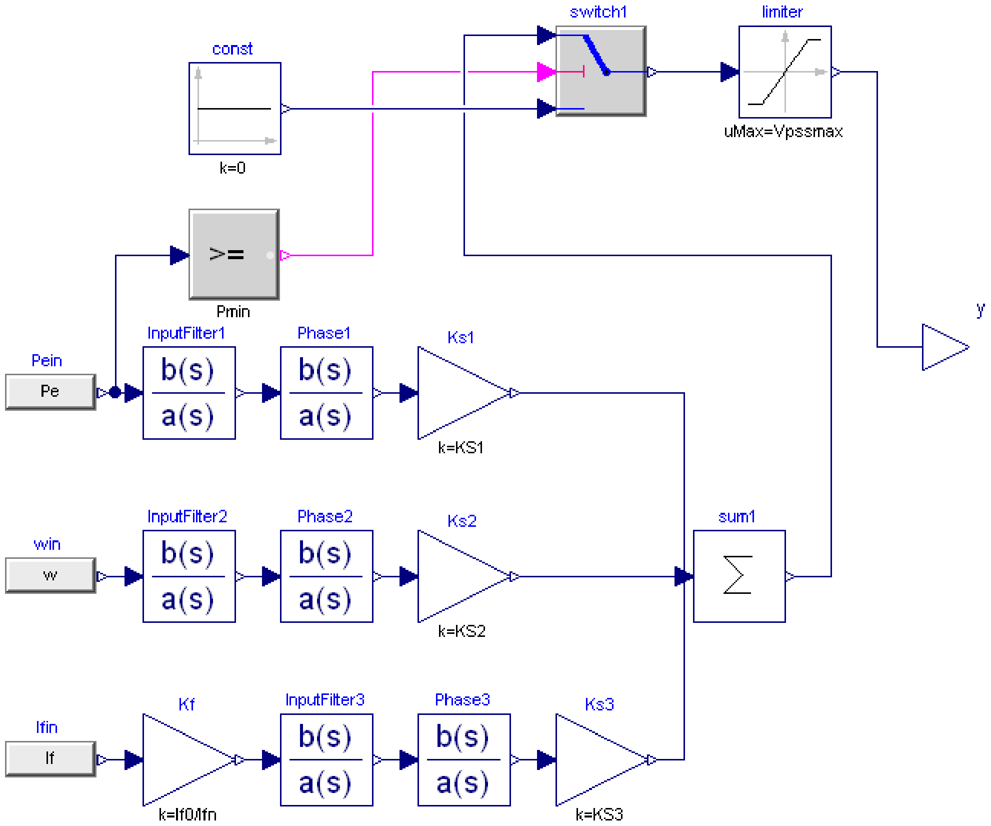

**Figure A-2: Model of the PSS**

Three signals are fed into the PSS: a) electrical power *Pe*, b) rotor speed *w* and c) field current *If*. All three signals run through input filters, phase compensators and linear amplifiers (*Ks1 – Ks3*) before they are summed in *sum1*. The resulting output signal at *sum1* is then subjected to upper and lower PSS output voltage limits in *limiter* before fed into the AVR.

The switch *switch1* sets the output signal to zero when the electrical power is below a threshold value defined as *Pmin*.

### A.3. Steam Turbine and Steam Cycle

Figure A-3 shows the steam turbine and steam cycle in Dymola.

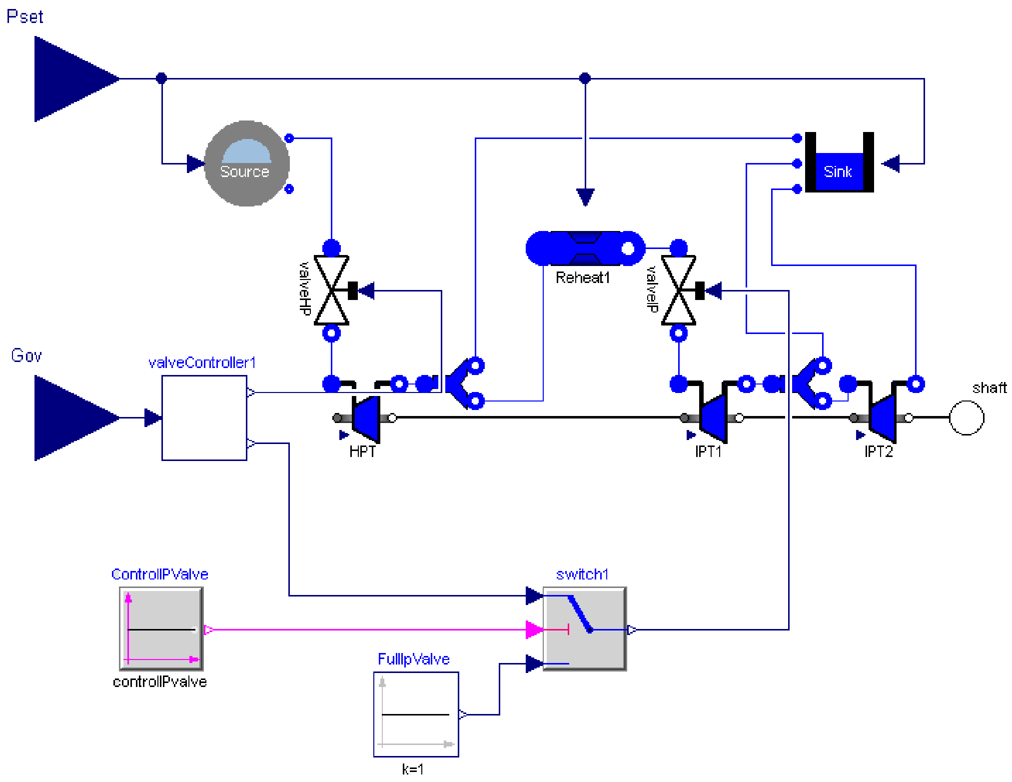

**Figure A-3: Steam turbine and steam cycle**

The model has two inputs, *Pset* and *Gov*. *Pset* is connected to the power set point and *Gov* to the output of the turbine governor. The valve controller, named *valveController1*, calculates the valve positions for the HPT and IPT valve, respectively.

The Boolean logic at the bottom of allows setting the IPT valve position to fully open, regardless of the governor output signal. When the Boolean variable *controlIPvalve* is set to ‘*one*’ or ‘*true*’, the governor signal is used for the IPT valve position. Conversely, when *controlIPvalve* is set to ‘*zero*’ or ‘*false*’, the valve is fully open during the entire simulation.

*Source* models the boiler with heat sources for both HPT and IPT. The IPT heat source may not be connected when a re-heater used, such as indicated with *Reheat1* in figure A-3. Dymola then automatically disregards this heat source and acknowledges that with a warning during the model compilation. The model named *Sink* models the steam extraction after HPT and in the middle of the IPT and the district heating system. *Source*, *Reheat1* and *Sink* are all dependent on the input signal *Pset*. Given this signal, these components find the respective values for pressure and temperature in implemented steam tables.

The models *valveHP* and *valveIP* model the valves at the HPT and IPT, respectively. They are both connected to the valve controller where they receive the valve position.

*HPT*, *IPT1* and *IPT2* act as the aggregated steam turbine model. These three turbine sub-models are connected via the shaft model and, thus, run on the same mechanical speed.

Flow splitters are connected to *HPT* and *IPT1* where a part of the steam is absorbed by the sink and the rest is further utilized in the turbine.

The mechanical connector *shaft* acts as the interface to the model of the inertia and eventually to the generator.

## A.4. Turbine Governor

Figure A-4 shows the model of the turbine governor.

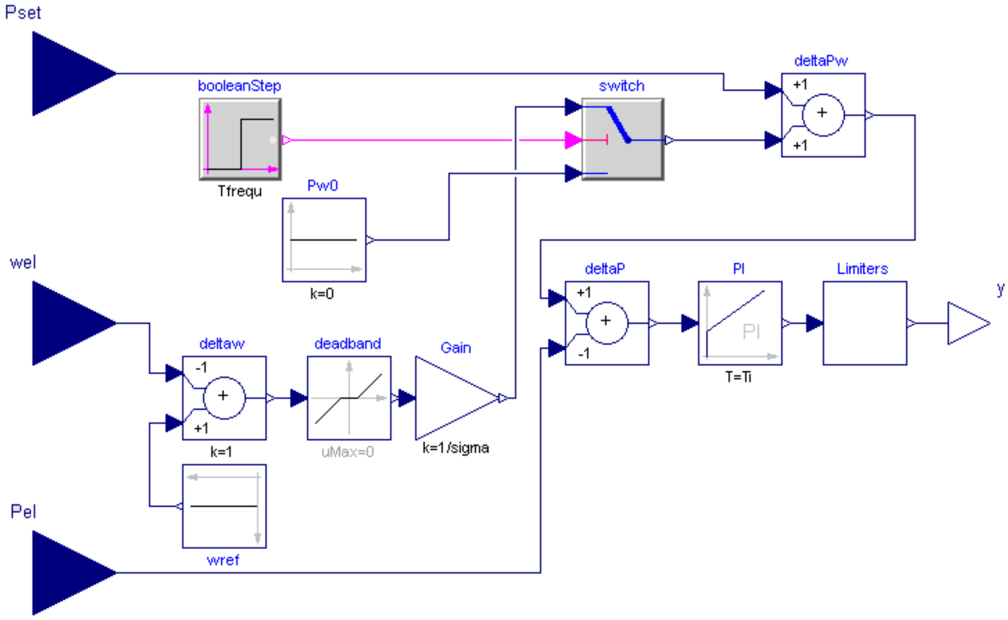

**Figure A-4: Model of the turbine governor**

The model of the turbine governor uses three inputs, namely *Pset*, *wel* and *Pel*. *Pset* is connected to the power set point, *wel* is the rotor speed and *Pel* is the instantly generated power at the generator.

The signal *wel* is first compared with its respective reference value *wref*. The difference is filtered by the block *deadband*. During the simulations, this block does not give any contribution. *Gain* then amplified the difference in frequency with the inverse of the static given by the parameter *sigma*.

The Boolean logic is used to enable and disable the impact of the frequency sensitive part of the governor. This feature was found to be important during the initialization of the model. The block *booleanStep* generates a step after *Tfrequ* seconds which activates the frequency sensitive part of the governor and allows the simulation of primary frequency control.

The input signal *Pset* is used a reference signal for power output at the generator. At *deltaPw*, the power set point signal and the additional contribution from a frequency deviation are summed. The output is then fed to the block *deltaP*.

At *deltaP*, the instantly generated power *Pel* is subtracted from the power set point plus the contribution from the frequency sensitive part. The resulting deviation is fed into the PI controller *PI*. The PI controller's output signal is fed in a block called *Limiters*, which is illustrated in figure A-5.

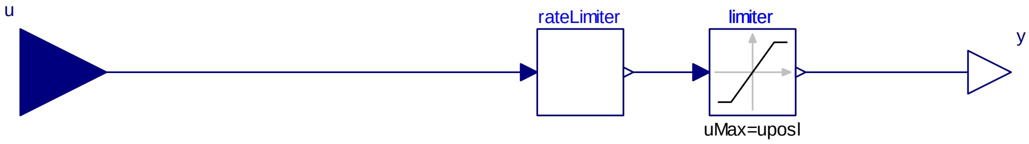

**Figure A-5: Limiter in the turbine governor**

The signal is fed into a rate limiter, see *rateLimiter* in figure A-4. This rate limiter permits just a defined change per defined time interval, i.e. is the derivative of the signal is subjected to limits. This simulates the restrictions on how quick a valve can be opened and closed, respectively. The block *limiter* limits the signal to its allowed minimal and maximal values, i.e. zero (0%) as the lower limit and one (100%) the upper limit.

## A.5. Open-Loop Test 1

Figure A-6 shows the test system for the open-loop test 1.

The turbine model *turbine* is connected to inertia model *inertia* via mechanical connectors. Furthermore, *inertia* is connected to the generator *gen* via mechanical terminals.

The generator is connected via electrical terminals to *PQ*, which models the power plant's own power consumption. This load is connected to the infinite bus *slack* via the transformer *Transfo*.

The governor, also named *governor* in figure A-6, receives two input signals from the generator, i.e. *wel* and *Pel*, see figure A-4.

Two power set point blocks are used, i.e. *PsetGovernor* and *PsetTurbine*. They both have the same initial value. However, *PsetGovernor* simulates an increasing ramp after a defined time interval given in seconds.

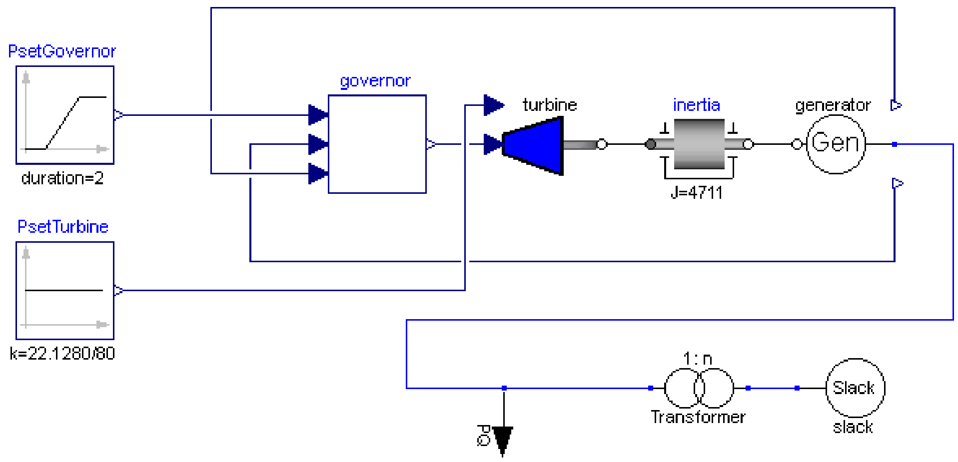

Figure A-6: Open-Loop Test 1 test system

## A.6. Open-Loop Test 2

Figure A-7 shows the test system for Open-Loop Test 2.

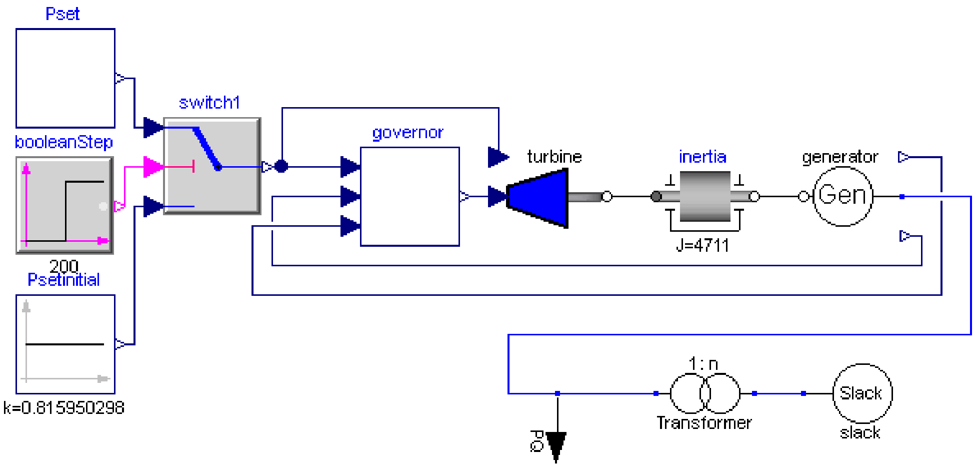

Figure A-7: Open-Loop Test 2 test system

The set up shown in figure A-7 is very similar to the one shown in figure A-6. Again, two power set block are used, i.e. *Pset* and *Psetinitial*. *Psetinitial* holds the first value of *Pset* and is active during the initialization of the simulation. A step applied after 200 seconds at *booleanStep* makes *Pset* the set point reference.

*Pset* contains a table with power set values correlated to time. In that way, the time varying power set point reference is simulated.

Another difference is that the power set point is connected to both *governor* and *turbine*. This set-up is due to the aim of simulating long term behavior, i.e. several hours. Within this time frame, the firing in the boiler is virtually changed by changing the power set value at *turbine* as well.

## A.7. Real Case Scenario Test

Figure A-8 shows the test system of the real case scenario test.

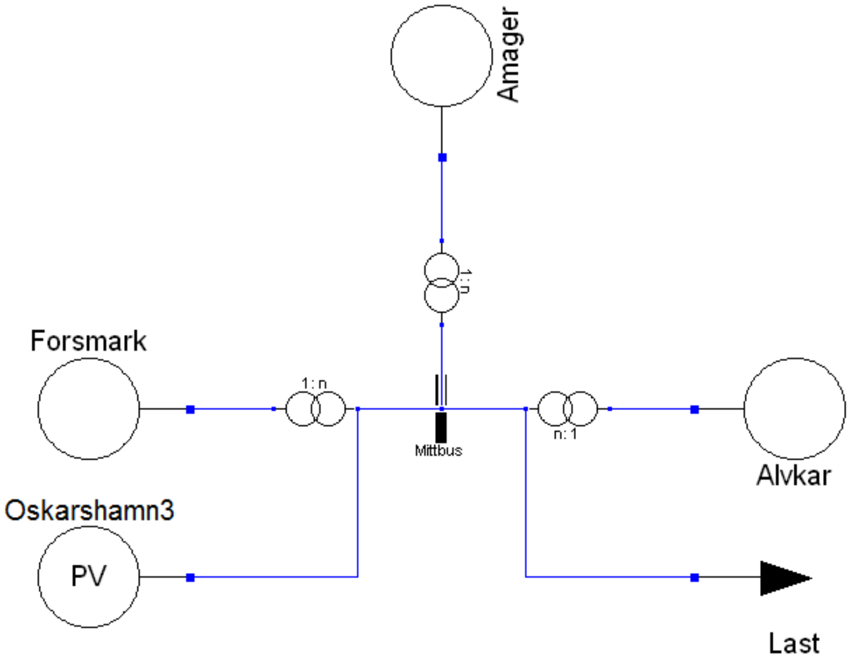

**Figure A-8: Real Case Scenario test system**

Figure A-8 illustrates a simplified model of the ENTSO-E RG Nordic power system which was used to simulate a drop in system frequency caused by the disconnection of block 3 of Oskarshamn nuclear power plant.

The generator *Forsmark* combines all base load power generation. *Forsmark* is equipped with a voltage regulator but does not have any turbine governor.

*Alvkar* combines all hydro power participating in frequency control. *Alvkar* has a voltage regulator and a turbine governor sensitive to system frequency deviations.

*Amager* models Amagerverket and is modeled as in the previous test systems, but with one, constant reference power set point. *Amager* is equipped with both a voltage regulator and a turbine governor responding to frequency deviations.

*Oskarshamn3* is modeled as a PV bus which is disconnected after a defined time interval. The time for the disconnection is given as a parameter in *Oskarshamn3* and, therefore, no breaker model is required for this purpose.

*Last* combines all load at the instance of the trip of Oskarshamn block 3 and accounts for active and reactive power consumption. The load model is both voltage and frequency dependent.

All generators, except for *Oskarshamn3*, are connected via step-up transformers to the virtual bus *Mittbus*.

# Appendix B Model Parameters

Important parameters for models and all three simulations are listed.

When no unit is stated, the parameter is given just as a number, e.g. gain values. Values for initialization are not presented.

Table B-1 lists parameters of the turbine governor model.

**Table B-1: Turbine governor model parameters**

| Parameter | Description | Value | Unit |
|---|---|---|---|
| sigma | Droop or static | 0.1 | p.u. |
| Ki | Governor proportional gain | 1.5 | |
| Ti | Governor integration time constant | 11 | s |
| urtlvsm | Rate limiter upper rate limit | 0.2 | p.u. |
| lrtlvsm | Rate limiter lower rate limit | -0.5 | p.u. |
| Tsvsm | Rate limiter time constant | 1 | s |
| uposlim | Limiter upper position limit | 0 | p.u. |
| lposlim | Limiter lower position limit | 1 | p.u. |

Table B-2 lists additional parameters relevant for Open-Loop Test 1.

**Table B-2: Parameters Open-Loop Test 1**

| Parameter | Description | Value | Unit |
|---|---|---|---|
| SystemSbase | Power system base power | 100 | MVA |
| governor.Tfrequ | Time after which frequency control is active | $10^8$ | s |
| turbine.ControlIPvalve | IP valve fully open (if false, IP valve is fully open) | true | Boolean |
| PsetGovernor.height | Change in power set point | 0.05 | p.u. |
| PsetGovernor.duration | Duration of the change in power set point | 2 | s |
| PsetGovernor.offset | Power set point for turbine governor | 0.2766 | p.u. |
| PsetGovernor.startTime | Time after which the change should apply | 500 | s |
| PsetTurbine | Power set point for turbine | 0.2766 | p.u. |

Table B-3 lists additional parameters relevant for Open-Loop Test 2.

**Table B-3: Parameters Open-Loop Test 2**

| Parameter | Description | Value | Unit |
|---|---|---|---|
| SystemSbase | Power system base power | 100 | MVA |
| governor.Tfrequ | Time after which frequency control is active | $10^8$ | s |
| turbine.ControlIPvalve | IP valve fully open (if false, IP valve is fully open) | false | Boolean |
| Psetinitial | Initial power set point | 0.8159 | p.u. |
| booleanStep | Enable Pset | 200 | s |

Table B-4 lists additional parameters relevant for Real Case Scenario.

**Table B-4: Parameters Real Case Scenario**

| Parameter | Description | Value | Unit |
|---|---|---|---|
| SystemSbase | Power system base power | 44000 | MVA |
| governor.Tfrequ | Time after which frequency control is active | 200 | s |
| turbine.ControlIPvalve | IP valve fully open (if false, IP valve is fully open) | true | Boolean |
| Pset | Power set point on generator base | 0.7 | p.u. |

## Calculation of Turbine Parameters

A number of turbine parameters were determined beforehand. These parameters include the Stodola coefficients, iso-entropic efficiencies and mechanical efficiencies for all three turbine sections.

Given the respective inlet pressure and temperature, the density of the steam can be determined. A convenient and uncomplicated way of doing this is to use steam tables. Here, the steam tables implemented in Modelica were used.

Given the density, mass-flow rate and inlet and outlet pressure levels, (3.18) can be solved for $k_T$.

$$k_T = \frac{\omega_{Turb}}{\sqrt{\rho_i p_i}\sqrt{1-r_s^{\,2}}}$$

Since all quantities are known, $k_T$ can be calculated.

The iso-entropic efficiency can be found via the in- and outlet enthalpies and the iso-entropic enthalpy. Solving (3.19) for $\eta_{ISO}$ gives:

$$\eta_{ISO} = \frac{h_i - h_o}{h_i - h_{ISO}}$$

The iso-entropic enthalpy can be found utilizing steam tables. First, the inlet entropy is determined using the inlet enthalpy and either inlet pressure or temperature. Second, taking this entropy and either pressure or temperature of the outlet steam, gives the iso-entropic enthalpy. Depending on the difference between inlet and outlet quantities, different steam tables may be utilized.

The mechanical efficiency was found by trial and error so that the delivered power under nominal conditions, i.e. nominal mass-flow rate and fully open valves, gives the rated power output.