Flexibilization of coal-fired power plants
by Dynamic Simulation

Marcel Richter[1]   Florian Möllenbruck[1]   Andreas Starinski[1]   Gerd Oeljeklaus[1]   Klaus Görner[1]

[1]Chair of Environmental Process Engineering and Plant Design, University of Duisburg-Essen, Germany
{marcel.richter, florian.moellenbruck}@uni-due.de

Abstract

Due to the strong expansion of renewable energies, the economical and technological boundary conditions for coal-fired power plants in Germany changed significantly over the last few years. Nowadays the flexibility in power production becomes increasingly important. This increasing flexibility requirement is caused by a more and more volatile residual load through the fluctuating power output from weather-dependent renewable energies such as wind power and photovoltaics. A similar trend can be observed in other European countries and even world-wide, where the expansion of renewable energies is pursued to reduce the emission of carbon dioxide. Dynamic simulation models play a central role in improving the flexibility of power plants as they offer a tool for the evaluation and improvement of the resulting highly transient operation. This paper presents the dynamic modeling of a coal-fired power plant in Modelica/Dymola using the power plant library *ClaRa* (Clausius-Rankine). The focus is on the detailed non-steady-state modeling of the steam generator and the validation of the dynamic simulation model. Additionally, first results of simulation studies about the integration of a thermal energy storage and the increase of the load change rate are presented.

Keywords: thermodynamics, dynamic simulation, steam power plant, flexible power plant, steam generator, validation, thermal energy storage, load change rate

1   Introduction

The share of renewable energies in power production in Germany increased significantly during the last years. This development has been supported by the German Renewable Energy Sources Act (EEG) which guarantees preferred feed-in into the electrical grid for renewable energies. The development of the power generation capacity in Germany between 2002 and 2012, shown in Table 1, illustrates the expansion of the renewable energies. The substantial growth of the total installed capacity from 127.0 to 184.4 GW is mostly covered through the renewable energies wind and sun (photovoltaics). The share of renewable energies in power production in Germany increased from 7 % in 2001 to nearly 25 % in 2013 [1]. According to the latest version of the EEG from August 2014 this development is to be continued towards the targets of 40 - 45 % in 2024, 50 - 60 % in 2034 and 80 % in 2050 [6].

Table 1: Power generation capacity in Germany in GW_{el} based on energy data [5] for 2002 and 2012 and on the assumptions of the Netzentwicklungsplan* (grid development plan) for 2024 and 2034 (scenario B) [7]

in GW_{el}	2002	2012	2024*	2034*
Hard coal	30.1	29.8	25.8	18.4
Lignite	21.6	24.2	15.4	11.3
Fuel oil	5.3	4.2	1.8	1.1
Gas	20.3	26.4	28.2	37.5
Nuclear	23.6	12.7	0	0
Water	8.9	10.4	14.7	15.7
Wind	12.0	31.3	67	97.3
Photovoltaic	0.3	32.6	56	59.5
Biomass	0.8	6.2	8.7	9.2
Other	4.1	6.6	5.2	5.0
Conventional	104.3	102.3	84.9	81.7
Renewable	22.7	82.1	138.6	173.3
Total	127.0	184.4	223.5	255

The requirements for a stable grid operation rise due to this growing share of renewable energies and the volatile character of their weather-dependent power production. The transformation of the electricity system leads to fundamental structural changes in the residual load, defined as the demanded power (load) minus a proportion of fluctuating power (e.g. from wind and sun).

Figure 1 shows the distribution of the residual load in the year 2012 as well as predicted values for 2024 and 2034. There will be periods in the future where the load is fully covered by the supply of the renewable energies. This leads to the appearance of negative residual loads. The shift of the residual load distribution towards lower values implicates the necessity for fossil fueled power plants to run at the lowest possible minimum load. Additionally, the requirement for fast and economic start-up and shut-down procedures can be derived from this figure, because conventional power plants have to perform

these procedures more often. A further aspect is that the maximum residual load in 2034 is still in a similar dimension in comparison to today. To ensure security of supply during periods of high residual loads as well, controllable steam power plant capacity has to be available – as long as not enough storage capacity (e.g. pumped storages, power2gas, etc.) is built-up to compensate the fluctuating power production of renewable energies.
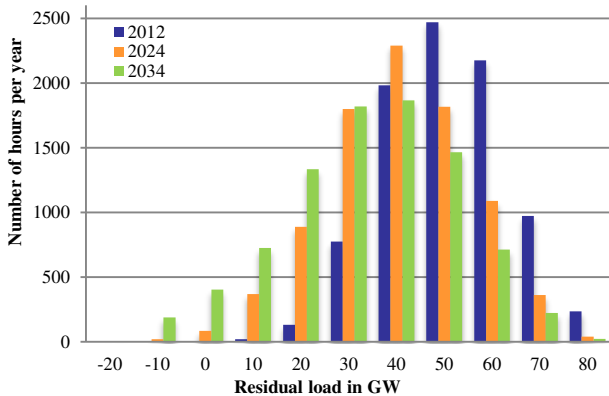

Figure 1. Histogram of the residual load in Germany (width of the histogram bars is ± 5 GW) [8]

Figure 2 shows the histogram of the residual load change between consecutive hours. The diagram illustrates a shift towards higher residual load changes for the future, both for negative and positive directions.
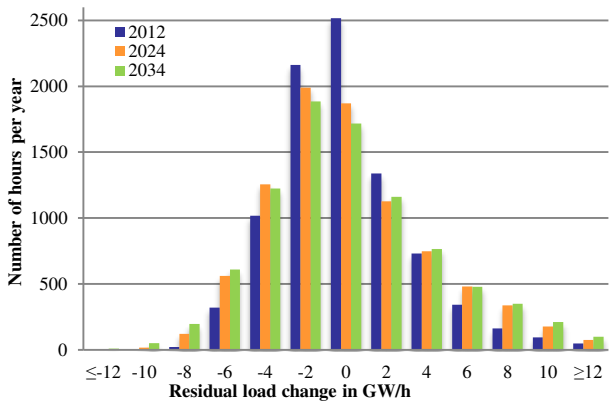

Figure 2. Histogram of the residual load changes between consecutive hours (width of the histogram bars is ± 1 GW/h) [8]

The rising volatility of the residual load results in increasing flexibility requirements to fossil fueled power plants regarding the load change rate, the start-up and shut-down procedures as well as the supply of control energy.

As a consequence of this development, the flexibilization of conventional power plants is one of the key challenges for the next years. This flexibilization is necessary to enable further integration of renewable energies while ensuring an economic operation of conventional steam power plants which ensure security of supply.

2   Applications of dynamic power plant simulation

Taking into account the future flexibility requirements to conventional power plants, the importance of dynamic power plant simulation increases. The dynamic power plant simulation offers a tool to model and calculate the transient operational behavior of existing or planned power plants.

The use of dynamic simulation models enables investigations about the following improvements in the power plant process [10]:

- Reduction of the minimum load
- Increase of the load change rate
- Reduction of the start-up and shut-down time
- Evaluation of the supply of control energy
- Evaluation of (thermal) energy storage concepts
- Evaluation of process quality during transient power plant operation

3   Simulation Software

ClaRa (Clausius-Rankine) is a free of charge and open source library of power plant components written in the modeling language Modelica. The library allows modeling and simulation of coal-fired power plants as well as heat recovery power plants, giving deep insight into their dynamic behavior [2], [3]. Both once-through and circulation boilers are supported. The library is structured component-wise including models for pumps, fans, turbines, heat exchangers, furnaces, electric motors, mills, valves, piping and fittings, as well as storage tanks and flue gas cleaning units. The library provides component models at different levels of detail supporting the user in creating system models tailored to their specific needs. The advantage of this concept is that the physical precision of a complex power plant model can be adapted to cope with the given simulation task without an unnecessary excess of computing time. The models are validated against literature and/or measurement data of existing plants, exemplified shown for the results of a pump in figure 3.
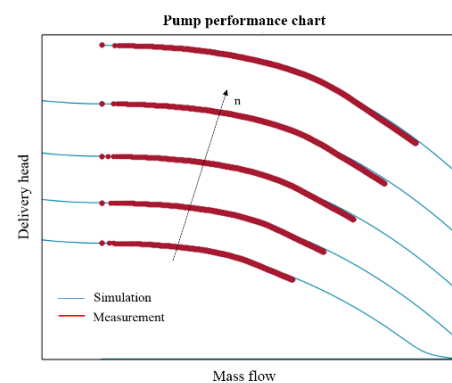

Figure 3. Validation results of a pump model

The library uses robust and fast media data from the *TILMedia* library as well as functions for pressure loss and heat transfer from the *FluidDissipation* library. In addition, special heat transfer correlations and radiation models are available for the flue gas path inside of a steam generator.

4 Modeling of steam power plants

Figure 4 shows the water-steam cycle of the modeled coal-fired power plant. This process flow diagram illustrates the three turbine groups (high, intermediate and low pressure turbine), the condenser, the feed water tank, the four low pressure and two high pressure preheaters and the subcomponents of the steam generator. The steam generator, as exemplarily shown later in figure 5, is an once-through boiler.

4.1 Procedure of model build-up

For dynamic simulations, the components of a power plant can be divided into steady and non-steady. The distinguishing criterion is the change rate of the component answering to a change in the thermodynamic boundary conditions (e.g. a change in temperature) reaching a new state of equilibrium. Table 2 shows the classification of the power plant components into steady and non-steady for the dynamic simulation model presented in this paper. Steady components have significantly smaller time constants in comparison to the non-steady components which means low influence to the dynamic behavior.

Table 2: Classification of power plant components into steady and non-steady based on [4]

Steady components	*Non-steady components*
Steam turbine	Heat exchanger
Pump	Steam pipe
Valve	Mixing point
Compressor	Feed water tank
..	Coal mill
	..

Based on this distinction, the procedure during the build-up of the dynamic simulation model can be divided into three steps, taking into account the difference between a steady-state simulation and a dynamic simulation. In the first step, a stationary simulation model with a detailed consideration of the steam generator (each heating surface is modeled and calculated) is developed using Ebsilon®Professional. The stationary simulation model provides the starting values for the parameterization and initialization of the dynamic simulation model, which is built-up in the second step using the power plant library *ClaRa* in Modelica/Dymola. The dynamic simulation model consists of the combination of steady and non-steady components based on table 2 and a detailed consideration of the implemented control structures.

In the third step, the dynamic simulation model is validated by comparing the calculated values with measured operating data of the underlying power plant. After successfully completing this step, the dynamic simulation model offers the possibility to perform investigations to improve the flexibility of the regarded power plant process.
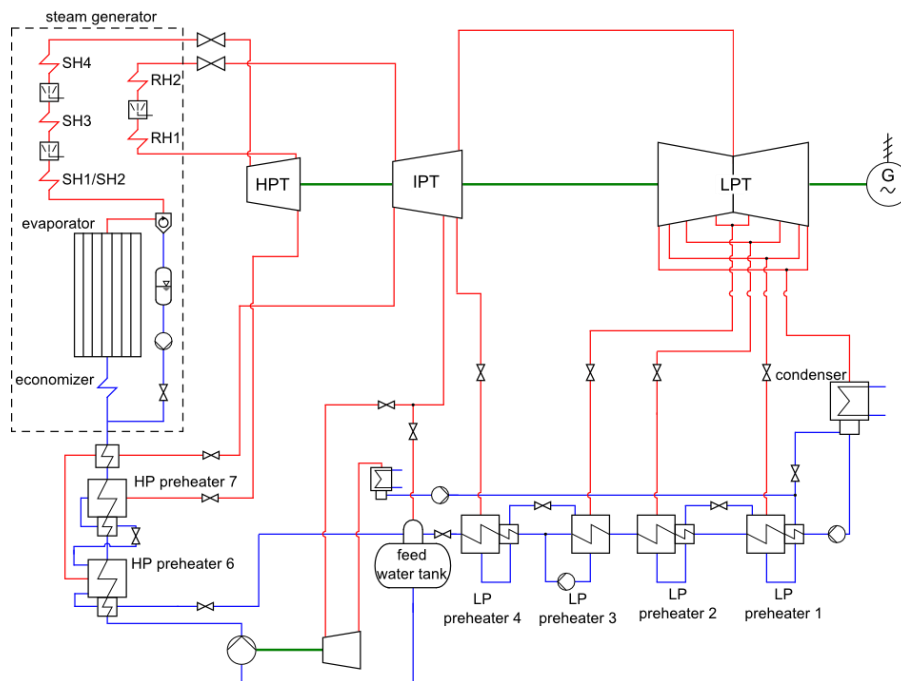

Figure 4: Process flow diagram of the modeled power plant

4.2 Detailed modeling of a steam generator

The structure of a detailed steam generator model within the *ClaRa* library is modular. The steam generator model itself can be divided into four areas:

1. Coal preparation and distribution
2. Flue gas path
3. Heating surfaces (walls and tube bundles)
4. Water flowing through the steam generator pipes

Figure 5. Exemplarily drawing of a steam generator [9]

Figure 6 illustrates the modular structure of the steam generator model in the *ClaRa* library. On the left side, the vertically discretized flue gas path is shown. The flue gas path is divided into several volume elements for every heat transfer section. Each component of the flue gas path can combine different functionalities, such as burner and/or heat transfer surface. Every component provides a model for the geometry, the velocity of coal and ash particles and the heat transfer correlation (e.g. radiative heat transfer within the flame room and/or convective heat transfer within the tube bundle heating surfaces).

The combustion chamber with the burners is represented by the component "Evaporator" at the starting point of the flue gas path. For the distribution of coal and combustion air, this component is connected with the coal and combustion air mass flow rates. The time-dependent behavior of the coal mills is represented by transfer functions. In flow direction of the flue gas the sections of a flame room (SH1) and the

tube bundle heat exchangers (SH2, SH4, RH2, SH3, RH1, ECO) are following. Each component in the flue gas path has a connector (red lines in figure 6) for the heat flow to the pipe wall. The components representing the sections for tube bundle heat exchangers have two additional connectors for the heat transfer to carrier tubes and tube bundle.
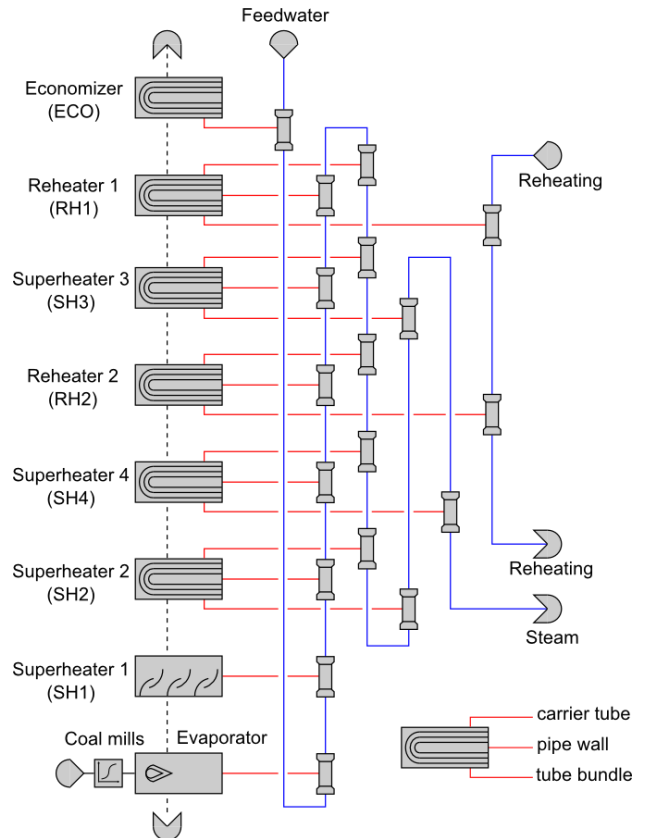
Figure 6. Modular structure of the steam generator

The material of the steam generator pipes is considered through a thin wall between flue gas and water-steam cycle, as exemplarily shown in figure 7. The tube-elements representing the water-steam side can be discretized by the user into several volume elements.
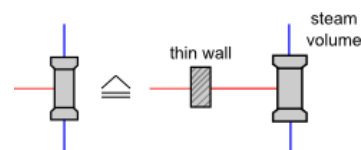
Figure 7. Wall-concept in ClaRa

The feed water initially flows through the economizer. This component is located at the end of the flue gas path and is connected in countercurrent. From the economizer the water flows through the downpipe drains to the evaporator. The following pipe wall (SH1) is arranged vertically and is modeled as a flame room. Subsequently, the steam flows through the three superheater surfaces of SH2, SH3 and SH4. The reheating takes place in the two reheater surfaces (RH1/RH2). Injection coolers are located between the surfaces of SH2/SH3, SH3/SH4 and RH1/RH2.

4.3 Control System

Besides the dynamic modeling of the power plant process, the control system has to be considered during the build-up of a dynamic simulation model. The control structures implemented within the control system have a major influence on the transient behavior of a power plant and consequentially also on the results of a dynamic power plant model. The goal of the power plant control system is the coordination of the interaction between boiler, turbine and generator to ensure efficient and safe operation of the power unit. The control system calculates setpoints and manipulated variables for the transient operation of a power plant. The entire control system has a high complexity and consists of a plurality of subordinate control loops for the command and control of various components and auxiliary units. The following control structures are implemented in the presented dynamic simulation model to achieve sufficient accuracy of the simulation results:

- Unit control
- Feed water control
- Steam temperature control
- Control of coal mills & fresh air

The main task of the unit control, shown in simplified form in figure 8, is to adapt the actual power output to the required target power output [12].
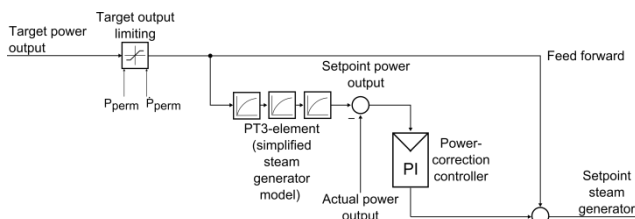
Figure 8. Simplified structure of the unit control implemented in the dynamic simulation model

To comply with the plant limits, the target output limiting ensures that the setpoint power output does not exceed the maximum permissible output P_{perm} and maximum permissible rate of change $\dot{P}_{perm}$. A step change of the target power output is thereby transferred into a straight line with the permissible rate of change $\dot{P}_{perm}$ (in MW/min) as the gradient. The time behavior of the steam generator (especially coal mills and heat transfer) is represented by a PT$_3$-element. Following this, the difference between setpoint and actual power output is given to the power correction controller which determines an appropriate correction factor.

Figure 9 illustrates the simplified schematic structure of the steam temperature control. The regulation of the live steam temperature to the setpoint is achieved through the injection of cool water in front of the surfaces of SH3 and SH4. The mass flow of water to the injection coolers is controlled by a cascade connection of two PI controllers [11].
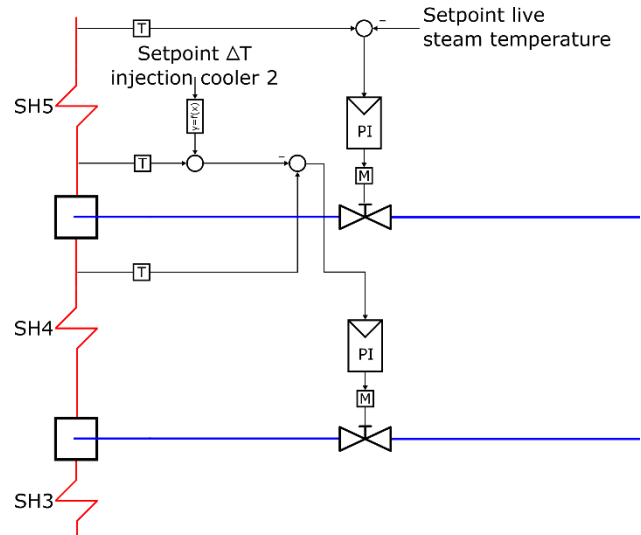
Figure 9. Simplified structure of the steam temperature control implemented in the dynamic simulation model

5 Validation against operating data

In order to prove the validity of the dynamic simulation model, measurement data from the underlying power plant are compared to the simulation results. The regarded load profile is characterized by several positive and negative load changes between minimum load and nearly full load.
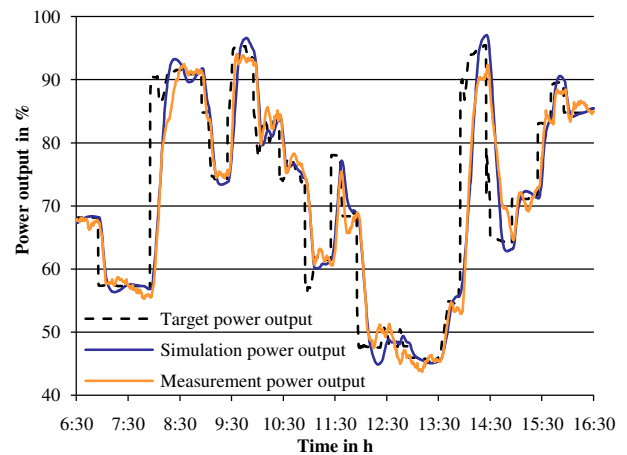
Figure 10. Comparison of the simulated power output (blue line) and measured values (orange line)

As described above, the power output is mainly controlled by the unit control with the target power output as the input variable (black dashed line). The results of the dynamic simulation model (blue line) show a high level of accordance to the measurement data (orange line) concerning the power output during the load profile. In particular, the rate of change during the load change processes is very well reproduced by the dynamic simulation model. This is due to the correct setting of the maximum permissible rate of change $\dot{P}_{perm}$ within the unit control, as presented in the previous section.
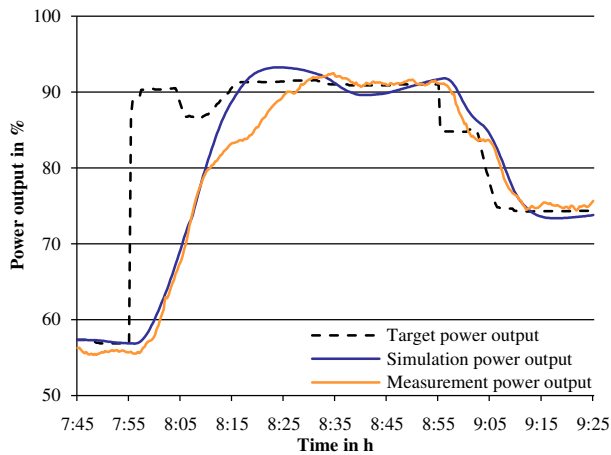
Figure 11. Comparison of the simulated power output (blue line) and measured values (orange line) between 7:45 and 9:25

Figure 11 shows a shorter section of this validation over a period of 100 minutes. In the time range between 8:15 and 8:35 a noticeable deviation has to be recognized between simulation and measurement. Due to a lower rate of change during this time range, the measurement data needs approximately ten minutes more to reach the target power output. This deviation can be explained by the fact, that the unit control implemented in the dynamic simulation model is a simplified structure in comparison to the highly complex structure of the underlying reference power plant. Here the authors see further development opportunities of the dynamic simulation model. Nevertheless, figure 11 shows that the power plant's dead and balancing times are simulated in a sufficient accuracy. Thereby, the dynamic simulation model is valid for the simulation studies about the integration of a thermal energy storage and the increase of the load change rate as presented later in section 5.
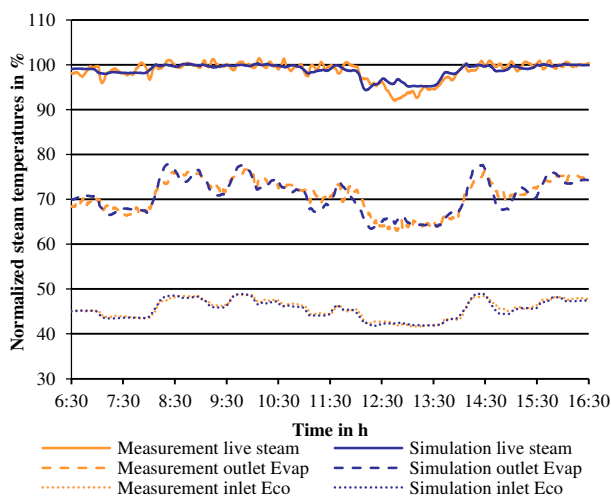

Figure 12: Comparison of simulated (blue) and measured (orange) water-steam temperatures

Figure 12 shows the comparison of simulated (blue) and measured (orange) water-steam temperatures to

prove the validity of the dynamic steam generator model. The diagram is normalized to the set value of the live steam temperature. The economizer inlet temperature, the evaporator outlet temperature and the live steam temperature show a good match between simulated and measured values during the load profile. Thereby, the detailed dynamic simulation model of the steam generator - as presented in section 4.2 - is proven successfully what can be claimed as a considerable achievement. Furthermore, the control of the live steam temperature to the set point confirms that the implemented steam temperature control is working sufficiently.
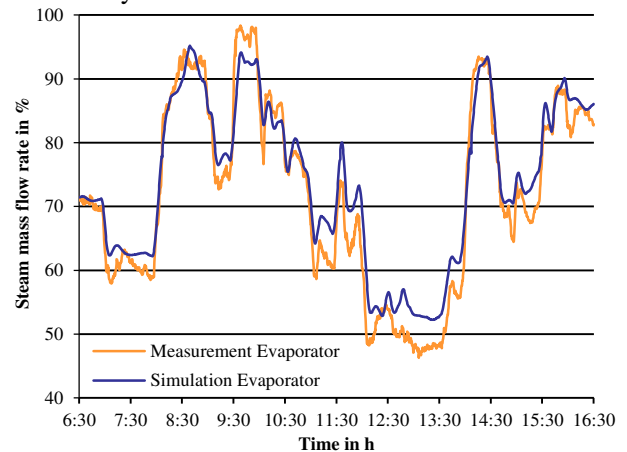

Figure 13: Comparison of simulated and measured mass flow of the evaporator

Finally, the time curve of the simulated evaporator mass flow, illustrated in figure 13, also shows a sufficient accuracy during the load profile.

Summing up, the comparison of simulated and measured values shows a good accordance in different load points and also during load changes. Thereby the validity of the dynamic simulation model is proven successfully and the model enables further investigations to increase the flexibility of the power plant process.

6 First results of the dynamic simulation model concerning flexibilization

6.1 Integration of a thermal energy storage

The integration of a thermal energy storage is one possible flexibilization measure that can be evaluated by the dynamic simulation model. A thermal energy storage can have different effects on the flexibility, depending on concept, point of integration and capacity. A thermal energy storage can be used to improve the power plant start-up procedure or to increase the load change rate. Furthermore, the integration of a thermal energy storage can offer the possibility of a load shift between minimum load and full load. If a power plant is operated in minimum load - usually in times with a low spot market price - the

storage can be charged with energy from the water-steam cycle. Thus, charging the storage results in a reduction of the electrical minimum load. In times of high spot market prices the energy from the storage can be integrated into the preheating route, leading to an additional electrical power output in full load by reducing bleed steam.

The integration of such a thermal energy storage system to the underlying power plant process is shown in figure 14. The storage is charged with energy from the cold reheat steam. During discharge-mode energy from the storage system is integrated between low pressure preheater 4 and the feed water tank.
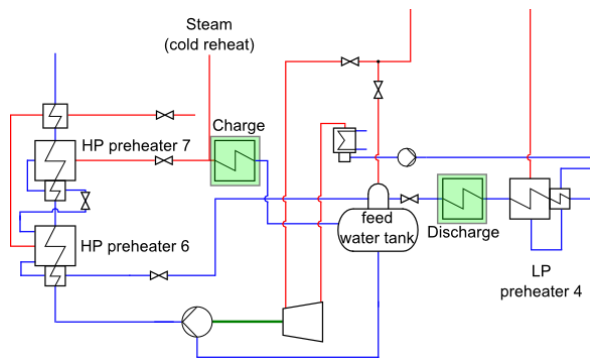

Figure 14. Extract of the process flow diagram with the integration of a thermal energy storage system

The integration of the thermal energy storage system has been realized by adding a heat consumer (charging) and a heat source (discharging) to the existing dynamic simulation model. To ensure reasonable results, a terminal temperature difference of 30 K was assumed. At this stage, the simulation stays conceptually and technologically open regarding design and used storage material. Figure 15 shows the results of the dynamic simulation model concerning the load shift between minimum load and full load as described above.
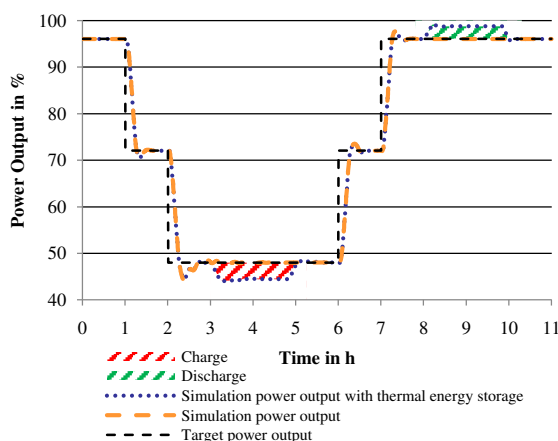

Figure 15. Simulation results for the load shift between minimum load and full load

Charging the storage system with a heat flow of 80 MW$_{th}$ leads to a reduction of the electrical minimum load in the amount of 3.7 percent. During discharge-mode the integration of 80 MW$_{th}$ enables an

additional electrical power output in full load in the amount of 2.8 percent. This corresponds to a thermal efficiency of the storage system of about 75 percent. The maximum heat flow is limited to 80 MW$_{th}$ to ensure the minimum mass flow rate of heating steam in the direction of the feed water tank (deaerator).

Based on these first results, the storage concept has to be designed in more detail in the next step. Furthermore, simulations about the increase of the load change rate by reducing the power plants dead and balancing time through the thermal energy storage system will be performed using the dynamic simulation model. Additionally, further concepts with the target of a multiple purpose storage will be developed. Multiple purpose storage means, that the concept is able to combine different flexibilization options (e.g. load change rate, primary control energy and start-up time/costs).

6.2 Load Change Rate

In this section, a simulation study is described showing a comparison of different maximum permissible rates of change $\dot{P}_{perm}$ within the unit control and the evaluation of the resulting load change rates of the power plant process.

Figure 16 describes the determination of the load change rate with the 90 percent method [12].
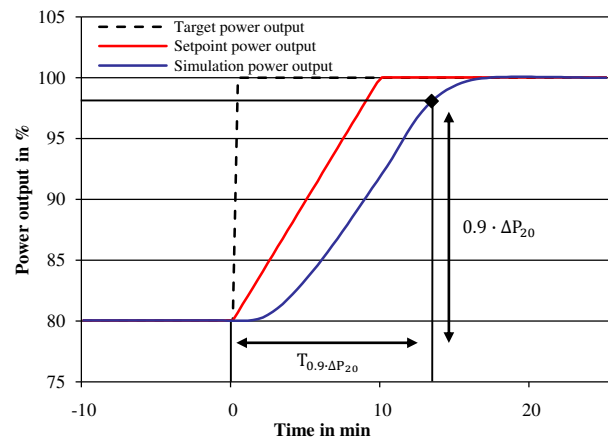

Figure 16: Determination of the load change rate with the 90 percent method

The calculation of the load change rate with the 90 percent method is based on the following equation:

$$\frac{dP}{dt} = \frac{0.9 \cdot \Delta P_{LC}}{T_{0.9 \cdot \Delta P_{LC}}} \tag{1}$$

where *LC* is the target load change in MW$_{el}$.

For the illustrated example shown in figure 16, the load change rate is calculated to

$$\frac{dP}{dt} = \frac{0.9 \cdot 20\ \%}{13\ \text{min}} \approx 1.4\ \%/\text{min} \tag{2}$$

That is 70 % related to the maximum permissible rate of change, represented by the red line in figure 16 ($\dot{P}_{perm} = 2\ \%/\text{min} = 100\ \%$).

Figure 17 shows the simulation results for a load change from 80 percent to 100 percent. The figure focuses on the period of 40 minutes, 10 minutes before and 30 minutes after the load change. The slow behavior at the beginning of the load change can be justified by the sluggish behavior of the process, in particular by the temporal behavior of the coal mills, the transport processes, the heat delivery and the heat transfer in the heating surface tubes. Due to the simplified implementation of the unit control, as explained in section 4.3, the simulated power output overshoots the target power output. Hence, the exact time curves have to be treated with caution. But the comparison of the configurations with three different maximum permissible rates of change $\dot{P}_{perm}$ is admissible.
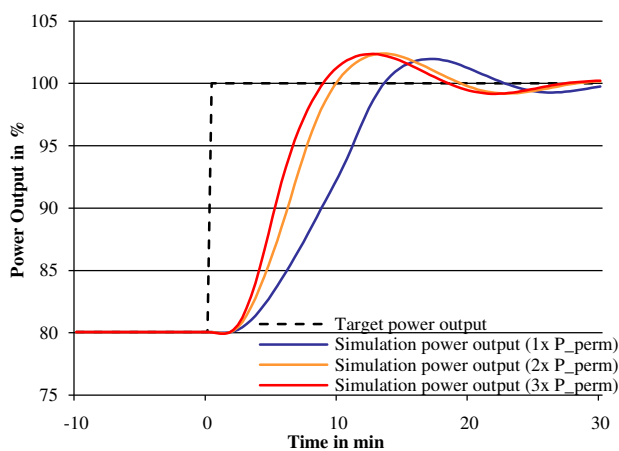

Figure 17. Comparison of the simulated power output with different maximum permissible rates of change $\dot{P}_{perm}$

The evaluation of the three different rates of change and the resulting load change rates (determined with the 90 % method) is presented in figure 18 for different load changes.
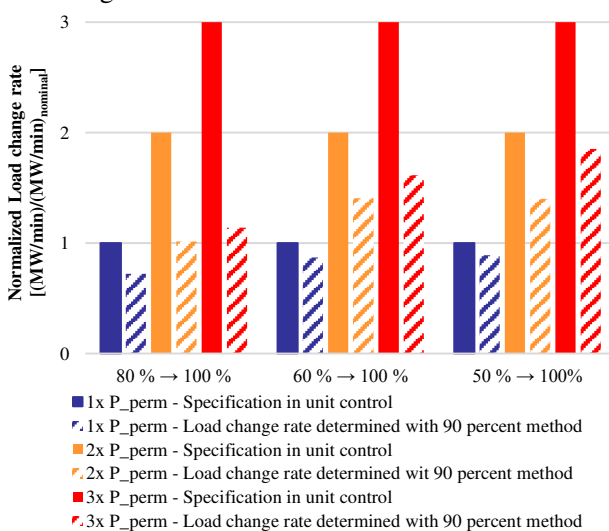

Figure 18. Evaluation of the resulting load change rates by specifying different rates of change $\dot{P}_{perm}$

It can be seen, that a doubling of $\dot{P}_{perm}$ in the unit control does not lead to a doubling of the achieved load change rate of the power plant process. This fact can be explained through the slow behavior at the beginning of the load changes. Furthermore, figure 18 shows that the load change rate is higher for higher load changes, as the influence of the inertia of the power plant process is getting smaller.

7 Summary and Outlook

Through the increasing share of fluctuating renewable energies in power production the operating flexibility of conventional steam power plants becomes increasingly important. Thereby dynamic simulation models are gaining in relevance as they offer a tool to evaluate measures to face the increasing flexibility requirements.

This paper presented the development of a dynamic simulation model for a coal-fired steam power plant with the open source library *ClaRa* with a focus on the detailed non-steady-state modeling of the steam generator. The results of the dynamic simulation model regarding the power output as well as the mass flow rates show a good accordance to operating data during a load profile. The validation of the detailed steam generator model was also proven successful by the comparison of water-steam temperatures during the load profile.

Furthermore, first results of the integration of a thermal energy storage system for a load shift between minimum load and full load were presented. The integration of the thermal energy storage system can lead to a reduction of the electrical minimum load during charging-mode and can supply additional electrical energy during discharge-mode in full load. In addition, first results regarding the variation of the maximum permissible rate of change $\dot{P}_{perm}$ were presented.

In the next steps, the dynamic simulation model will be developed further, especially regarding a more detailed implementation of the unit control and the extension of the thermal energy storage evaluations towards multiple purpose storages. Also further simulations about possible flexibilization measures regarding the improvement of the start-up procedure, the increase of the load change rate or the supply of (primary) control power will be performed with the dynamic simulation model.

Acknowledgements

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