Dynamic System Simulation for New Energy Markets – Optimization of a Coal Fired Power Plant Start-up Procedure

Timm Hoppe, Jan Braune and Lasse Nielsen

Kurzfassung

Dynamische Systemsimulation für einen sich wan-delnden Energiemarkt - Optimiertes Anfahren eines Kohlekraftwerks

Im Umfeld eines sich wandelnden Energiemarktes ergeben sich neue Herausforderungen und Betriebsweisen für konventionelle Kraftwerke, welche die fluktuierende Einspeisung erneuerbarer Energien teilweise kompensieren müssen. Dynamische Systemsimulation kann als kostengünstiges und unterstützendes Werkzeug in allen Projektphasen genutzt werden, um Fragestellungen zu beantworten, welche sich aus den neuen Anforderungen ergeben.

Im Folgenden Beitrag wird die in Modelica programmierte Kraftwerksbibliothek ClaRa+ und ihre möglichen Einsatzbereiche vorgestellt. Die Bibliothek entstand im Rahmen der vom Bundesministerium für Wirtschaft und Energie geförderten Projekte DYNCAP und DYNSTART.

Anhand des detaillierten Modells eines aktuellen Steinkohlekraftwerks werden die Mög-lichkeiten und Vorteile der dynamischen Systemsimulation verdeutlicht. Im Rahmen des Anwendungsbeispiels wird gezeigt, wie die vorgestellte Software genutzt werden kann, um den Anfahrprozess zu optimieren und so den Brennstoffverbrauch zu reduzieren, ohne die Stressbelastung in den dickwandigen Bauteilen zu erhöhen und in den laufenden Betrieb der Anlage einzugreifen.

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Introduction

Electricity production from renewable energies, such as wind and sun is continuously increasing. The combination of their fluctuating generation and priority feed-in is resulting in new operating modes for conventional power plants. Dynamic system simulation can be used in all project phases, from early design to optimization during operation, to solve problems arising from this changing energy market in a cost-efficient manner.

The Modelica library ClaRa/ClaRa$^+$ for dynamical simulation of power plants enables the user to build up digital twins of different kinds of power plants quickly and efficiently. This is beneficial, for example, to optimize the controller system, evaluate concept variants, or even analyze potentially dangerous or component-damaging operation conditions without disturbing the daily operation of the plant.

In the following, the ClaRa/ClaRa$^+$ library is presented through a use case that deals with the improvement of the start-up procedure of a large-scale power plant.

In engineering projects, different modeling and simulation techniques are often used to gather information on an existing plant or a new plant design. Steady state or flow sheet simulators are used to coarsely simulate a concept during the pre-design phase in order to analyze its performance for different layouts or to proof its feasibility under the given market situation. Therefore, the thermodynamic states at different plant locations are calculated using heat and mass balances mostly without detailed information on geometry parameters.

A more detailed simulation technique is the method of computational fluid dynamics (CFD) in order to dynamically simulate individual components or only parts of them to obtain detailed information on the distribution of temperatures and flows inside a predefined geometry.

The methodology of dynamic system simulators can be classified somewhere between the two techniques mentioned above. It is used to predict the dynamic behavior of the plant using more information about geometry than flow sheet calculations but a coarser discretization scheme than CFD. Such models can be used for a broad scope of applications. Some examples are given in section 2.3.

The ClaRa/ClaRa$^+$ library

In the following chapters the library ClaRa/ClaRa+ will be described in more detail. This includes the history of its development, its structure and an introduction to different fields of application in the form of use cases.

Background

One of the most recent software tools in the field of dynamical simulation of power plants is the ClaRa$^+$ library, which is developed since 2011 in a collaboration of Hamburg University of Technology, TLK-Thermo GmbH and XRG Simulation GmbH within the DYNCAP[1] project. The first official release version 1.0.0 dates from March 2015. The aim of this development was to provide a software that is both suitable for beginning and advanced users in the field of system simulation. Within the follow-up project Dynstart[2], new features have been added and the library was enhanced to handle extra-low-loads as well as start-up and shut-down processes. Out of the projects, the commercial version ClaRa$^+$ evolved with an extended scope, featuring, for example, additional component models and mediums, more detailed heat transfer models as well as additional libraries for controllers and grid components. A demo version of this library is available at www.powerplantsimulation.com

[1] Funded by the German Ministry for Economic Affairs and Energy under reference number FKZ 03ET2009.

[2] Funded by the German Ministry for Economic Affairs and Energy under reference number FKZ 03ET7060.

The structure of the library follows a functional approach and components of the same functionality, for example heat exchangers for different types of media, are located within the same package. The component models are used to build up cycle models by drag and drop, which could then be parametrized and simulated. The organization of the library packages containing these different types of models is explained in the following section 2.2.

Modeling is usually based on a first-principle modeling approach, capturing the important physics and enabling the user to model not only normal operation but also failure cases as well as shut-down and start-up processes without violating physical laws like mass and energy balances.

By using the object-oriented and equation based modeling language Modelica, which was developed to describe complex physical systems, the already comprehensive library can be easily extended by own models.

Library structure

Figure 1 Verweisquelle konnte nicht gefunden werden. gives an overview of the library's bundle structure. The **ClaRaPlus** library is "the core" of the bundle. The UsersGuide provides a brief introduction to the library and information on the revisions. The package Examples provides a number of introductory examples making new users familiar with the capabilities of the library. The package Basics contains basic models and other internally used codes like functions, records and interfaces. The package Components contains all the component models required to build up a power plant model, for example, turbo machines and electrical machines, connecting pipes, heat exchanger, mass storage and steam separation, valves, coal grinding, furnace, flue gas cleaning, gas turbines, a cooling tower and sensors. The package SubSystems contains some examples for the definition of subsystems and aims to introduce ideas for efficient teamwork. The package Visualisation offers possibilities to visualize the results. Finally, the package StaticCycles contains simplified, static and parameter-based models of most of the power plant components.

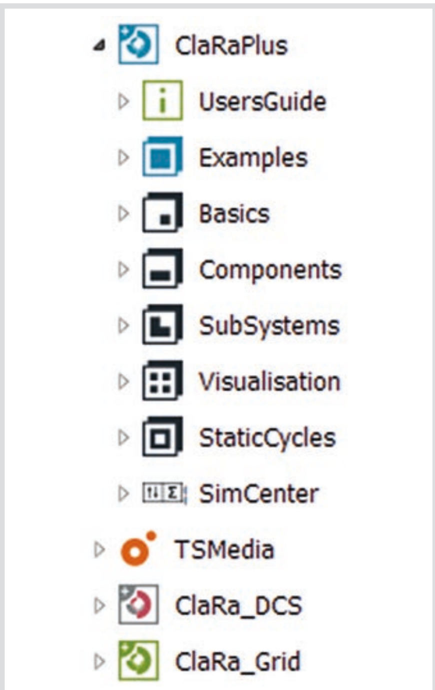

Fig. 1. Library structure of the ClaRa.

The **TSMedia** is a comprehensive substance property library which enables the user to use different types of property models, which were developed with a focus on accuracy, robustness and computational speed. A property model for pure Helmholtz fundamental equations of state and also table based spline interpolation is available for real fluids (VLEFluids) like water/steam. The interpolation data is available for different substances, which are recommendable concerning simulation speed and simulation stability, see [Schulze 2014]. The flue gas is described by an ideal gas-vapor mixture with ten substances, capable to handle condensation of water. The TSMedia features also numerous other mediums, for example pure CO_2 or other substances for ORC applications.

The **ClaRa_DCS** (**D**istributed **C**ontrol **S**ystems) library enables fast and efficient modeling of the power plant's control system. It provides ready-to-use feedback and feedforward blocks and examples showing their usage. Furthermore, it contains basic mathematical, logical and continuous blocks for custom controller modeling.

The **ClaRa_Grid** library contains electrical components such as switches, consumer grid models, transfer function based power plant models and many more. These models calculate the electrical boundary conditions imposed by an island or a national grid on the power plant.

In The following, different exemplary fields of applications are described for which the library could be applied.

Fields of application

The ClaRa$^+$ Software is used for a broad scope of applications and can support all project phases with dynamic simulations: from the evaluation of concept variants to component design, optimization of control technology, virtual commissioning and optimization during operation. In the following, some use cases with references are presented:

– System operation optimization. Classical application of a digital twin. It enables experiments which are not possible to conduct in the real plant. The model can be used, for example, to investigate different load ramps, disturbances or malfunctions, improve controller parameters and conduct "what-if"- studies with changed process design [Koltermann et al. 2018].
– Development of control strategies. Advanced, sophisticated control methods and new control strategies can be studied without interference of the real process. The power plant model serves as a test bench for different concepts [Gottelt et al. 2012].
– Design and verification of design. Components can be designed and their sizing verified within the process, under dynamic conditions. New process design concepts and their system integration can be set up, their interconnection with the control system and other parts of the plant can be studied [Vojacek et al. 2019], [Richter et al. 2019].
– Virtual commissioning. Prior to the commissioning of a newly built plant, the process model is combined with a model of the decentralized controller system. With help of this combined model, the controller parameters can be pre-tuned, shut-down and start-up sequences tested and optimized, critical interferences of controller loops identified and failure scenarios investigated. In consequence, the commissioning time can be significantly reduced and production at site starts earlier.

Even though the ClaRa was originally developed for modeling and simulating conventional coal fired power plants in combination with carbon capture and storage technology [Brunnemann et al. 2012], nearly all possible types of thermal power plants are featured with the current version of ClaRa$^+$. It allows modeling of lignite and hard coal power plants, combined cycle and cogeneration power plants with different types of boilers (e.g. once-through or natural circulation). With the broad media data base of the TSMedia, also other conversion cycles like supercritical CO_2 or Organic Rankine cycles are within the scope of the software. Due to the libraries versatility and easy extendibility, it was also used for modeling solar thermal power plants and geothermal plants.

Use Case

Informative background

This study has been carried out within the joint research project DYNSTART, which is partly funded by the German Federal Ministry for Economic Affairs and Energy and three major energy suppliers. Besides enabling the ClaRa library to simulate start-up and shut-down procedures, its aim is to find measures to flexibilize a state-of-the-art large scale power plant to be prepared for its future role in the European energy market. The study of one of these measures is presented in the following.

Problem description

The use case presented deals with the fuel consumption of a pulverized coal power plant during its start-up procedure. Since high primary air temperatures are needed to dry the raw coal in the mills and a flue gas temperature of around 600 °C is required to ignite the coal dust in the steam generator, a conventional coal fired power plant cannot be started up from a cold state by coal fire. Therefore, gas or heavy fuel oil burners are additionally installed for ignition and back-up. Both of these fuel types are significantly more expensive than raw coal. Hence, there is an incentive for the operator to reduce the amount of back-up fuel needed for start-up.

During start-up, when the back-up fuel burners have been ignited, the process medium is actuated in the evaporator by circulation pumps. As temperatures rise, the process medium starts boiling. The turbine bypass stations are opened to limit the pressure gradient in the system and to supply cooling steam to the superheaters and reheaters. Since the steam leaving the steam generator carries a temperature- and pressure-dependent amount of energy and is precipitated in the condenser, it can be interpreted as an energy loss. A reduction of this loss can be achieved by reducing the relative valve opening, causing a decreased mass flow through the bypass station as proposed by [Lens 2014]. Assuming a constant heat input of the oil burners, this would lead to a higher pressure gradient of the process medium. Hence, the pressure must be controlled by correcting the heat input. Furthermore, a lowered steam mass flow rate within the superheater and reheater piping induces a potential risk of overheating the material when the heat fluxes on the flue gas side reach critical values.

Model development

To account for the above mentioned potentials and risks, a detailed model of a hard coal fired steam power plant is developed. The ClaRa software provides generic models for all process components of a power plant. These models usually base on a first-principle modeling approach, thus capturing the important physics and enabling part load, start-up and shut-down simulations. The geometric data of a large scale German power plant have been used to parametrize these models.

The steam generator is discretized in 1D on the water/steam and the flue gas side, enabling the temperature and pressure distribution along the flow path of the two mediums to be captured. The discretization is based on the functional areas of the steam generator (e.g. economizer, burners, evaporator, superheaters and reheaters). Each functional area on the water/steam side is represented by a pipe model. Each pipe is thermally coupled via a wall model to the corresponding functional area on the flue gas side. One pipe model is added upstream and another pipe model is added downstream of each heat exchanger, representing the distributor and header respectively. The heat transfer between flue gas and pipe walls is modeled using the detailed heat transfer correlations for radiation and convection provided by the library. Spray injectors are considered as ideal mixing volumes. The steam turbine stages are modeled using Stodola's law. The system also includes models for mills, a regenerative air preheater, fans and simplified flue gas cleaning components.

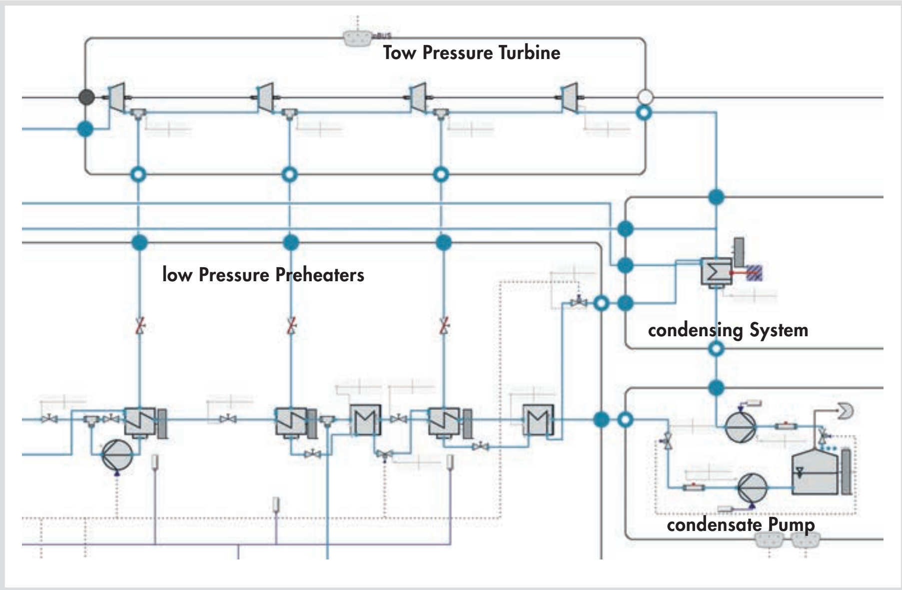

Fig. 2. Screenshot from the ClaRa GUI.

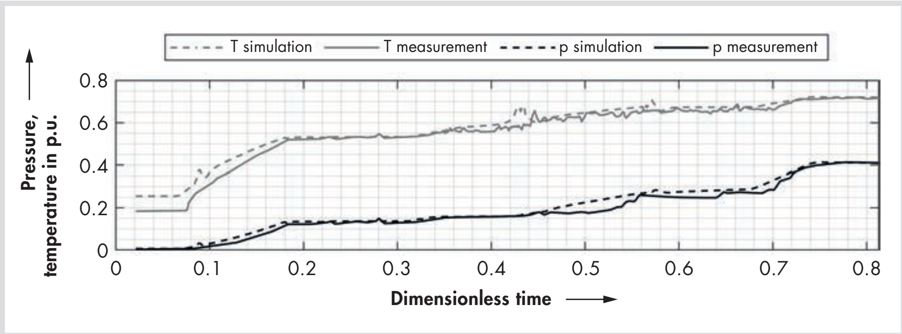

Fig. 3. Fluid temperature and pressure at the evaporator outlet.

The control system is implemented as required for the simulation of start-up procedures. The ClaRa_DCS provides the functional blocks to build a digital twin of the control system. Besides the fundamental control structures (e.g. steam pressure controller, feed water controller etc.), several discrete switching actions take place, especially during start-up (e.g. change fuel from oil to coal fire in a burner level). These switching actions are usually triggered by so called step-chains, a simplified version of which has been implemented in the model using the Modelica StateGraph2 library. To give an idea of the resulting model, a screenshot of the graphical user interface (GUI) is shown in Figure 2. This figure shows the low pressure part of the power plant model, including the last turbine stages, the condensate system and the low pressure preheaters with their interconnections to the adjacent parts of the power plant and to the control system.

Validation

The model is validated using measurement data from a start-up procedure. Figure 3 shows the fluid temperature and pressure at the evaporator outlet.

In the beginning of the start-up, the model tends to slightly overestimate fluid temperatures. This is because the fluid in the simulation is started under boiling conditions, while the fluid in the reference plant is slightly below the boiling temperature at this time. In the following time, gradients and absolute values show a good alignment with measurement data. Larger differences in fluid pressure between simulation and measurement occur only in the latter part of the time span shown. Here, set values from the set point controller have been simplified to reduce the modeling effort. A more general evaluation can be carried out as shown in Figure 4.

Here, simulation and measurement data have been equidistantly discretized in time. The difference between those values in a certain time step is classified in the form of a histogram. The more bulbous the histogram and the smaller the maximum devia-

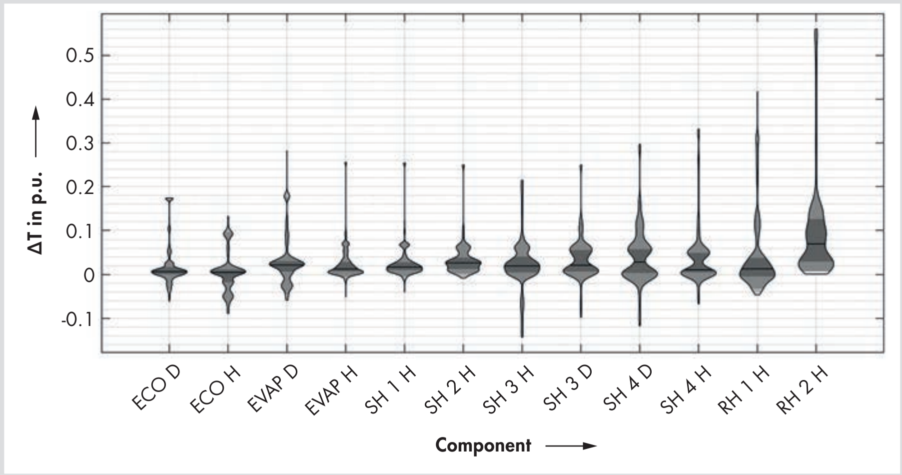

Fig. 4. Histogram of the deviation between simulation and measurement temperature data for different thick walled components of the steam generator.

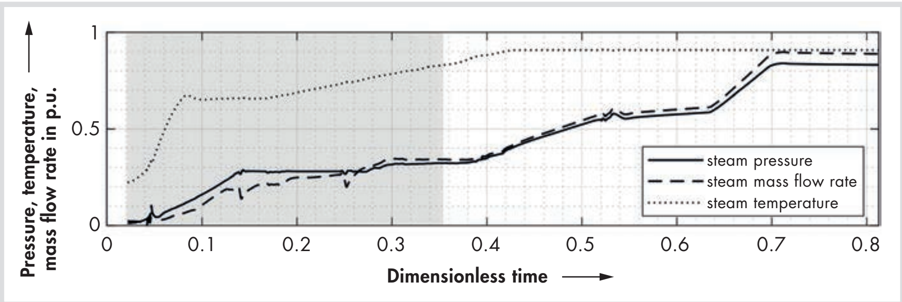

Fig. 5. Live steam parameters during start-up (reference case).

tion, the more accurately the model predicts the reference plant. The black line shown depicts the median of the deviation during the simulation time span. 50 % of the time the deviation is less than the dark gray marked span (95 % for the light gray marked area, respectively). The model shows good overall agreement with the measurement data, especially for the high pressure components (**ECO**nomiser, **EVAP**orator, **S**uper**H**eater). For those components, the median has a maximum deviation of 3 % of the nominal value. 50 % of the time, the deviation is within -2 % and +6 % of the nominal value. Similar diagrams have been generated for pressure and mass flow rates. In total, the model has been qualified to predict the reference plants behavior correctly.

Simulations

The results of the simulation concerning live steam parameters are presented in Figure 5.

In time step 0.04, the oil burners in burner levels 1 and 2 are ignited and set to a constant heat input. The bypass valves are opened according to a specified procedure. With the ongoing energy transfer into the system, steam pressure and steam temperature rise. The higher the steam pressure gets, the more steam passes the bypass valves resulting in an increasing steam mass flow rate at the steam generator exit. Figure 6 shows the energy balance of the steam generator during the gray marked period of time in Figure 5, where the energy storage term dU_{SG}/dt is calculated via equation 1.

$$\frac{dU}{dt} = \sum \dot{H} + \sum \dot{Q}_F \quad (1)$$

In minute 0.14, the oil burner in level 2 is superseded by coal fire. Hence, the oil heat input is reduced in order to keep the overall heat input constant at that level. In time step 0.17, the steam turbine is set into operation by slowly opening the turbine valve to a defined value. It reaches a fully opened state at time step 0.29. The energy storage term of the steam generator shows a major peak in the beginning of the start-up procedure. In the following minutes, it settles down to 0. Around time step 0.125, the steam generator is completely warmed. The heat input fed into the system no longer has a positive effect on the start-up procedure and is directly dissipated in the condenser. The surplus energy fed into the system is marked in gray in Figure 6.

In a second simulation run (see Figure 7), the relative opening of the turbine bypass is lowered and kept constant throughout the first 0.09 time steps of the start-up routine. The oil heat input is controlled by a simple control circuit in a way that the pressure gradient in the steam generator is the same as in the reference case.

Due to the reduced mass flow leaving the system, the heat input approaches the energy storage in the steam generator. Around time step 0.13, the bypass valve is opened with a constant gradient to increase the oil heat input. This approach was used to make the system converge with the reference case. The gray marked area in Figure 7, again, depicts the surplus energy fed into the system. Compared to the reference case in terms of heavy fuel oil usage, a reduction of around 22 % can be reached.

To account for lifetime consumption, a post-processing routine based on [DIN 12952] is implemented. The cyclic strain fatigue is calculated using the sum of pressure induced stresses (see equation 2)

$$\sigma_p = \alpha_m \frac{p \cdot d_{ms}}{2 e_{ms}} \quad (2)$$

and temperature gradient induced stresses (see equation 3)

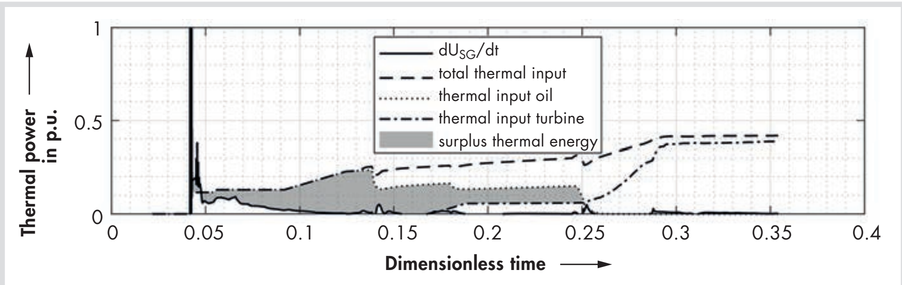

Fig. 6. Energy balance of the steam generator (reference case).

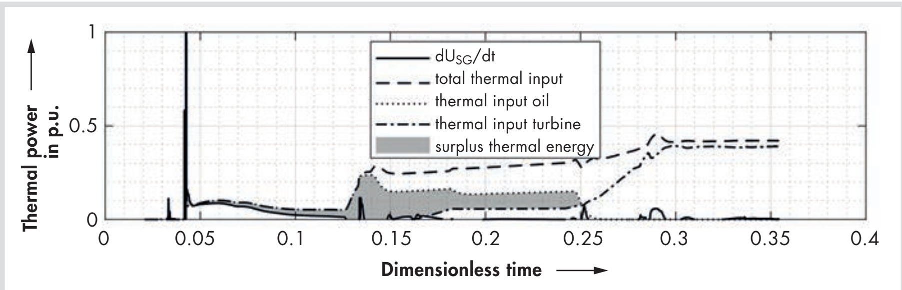

Fig. 7. Energy balance of the steam generator (alternative control case).

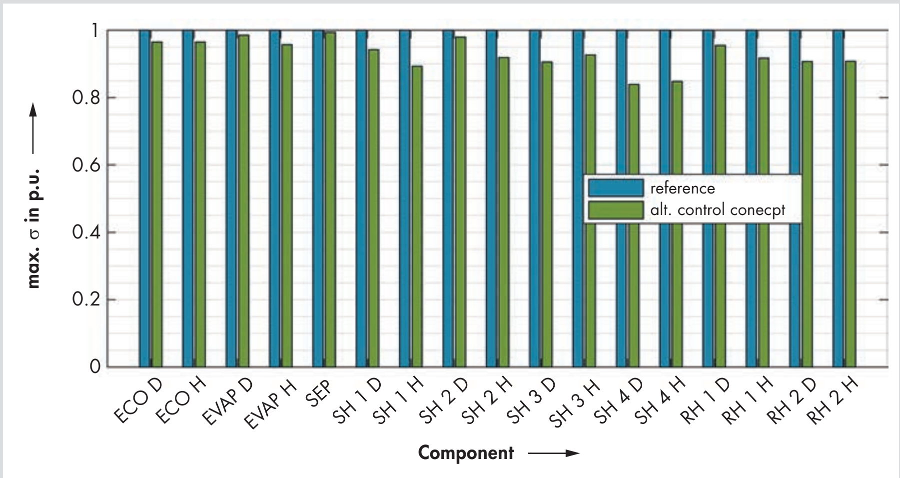

Fig. 8. Relative comparison of the maximum stress range of the two scenarios.

$$\sigma_T = \alpha_T \frac{\beta_{LT} E_T}{1-\nu} \Delta T_W \quad (3)$$

Figure 8 illustrates a relative comparison of the maximum stress range (see equation 4)

$$max.\sigma_{2a} = \max(\sigma(t)) - \min(\sigma(t)) \quad (4)$$

of the two scenarios presented, as this is a good indicator for cyclic strain fatigue. For all components shown, the alternative control concept causes a lower maximum stress range. Therefore, savings in fuel costs are not counteracted by increased maintenance costs.

Conclusion

Simulation techniques can be used as a cost-effective method to support engineering projects during all project phases by creating a digital twin of a power plant providing more information about the system than measurements. Therefore, this paper discusses the current status of the ClaRa$^+$ library and gives an overview of its overall scope and possibilities. As application example, a use case is presented which shows the potential of dynamic system simulation and how it is applied to improve the start-up procedure of a large scale power plant.

For the use case, a detailed model of a state-of-the-art hard coal fired power plant is used, which is developed using the ClaRa library and validated against measurement data. In this paper, a measure to improve start-up procedures, as proposed by [Lens 2014], is implemented and evaluated concerning savings in fuel consumption and cyclic strain fatigue on thick walled components. It is shown that, with the proposed changes in the control structures, up to 22 % of heavy fuel oil could be saved during start-up, keeping cyclic strain fatigue on thick walled components constant or lowered compared to the reference case.

Besides start-up procedures, the model is also used to simulate load changes in the upper load range to investigate the effects of higher load gradients on the plant's dynamic behavior and the wall stresses of crucial components. Also in the upper load range, the model allows to investigate the plant's capability to provide secondary control reserve depending on different control strategies of the coal mills. Additionally, advanced control strategies like model predictive control (MPC) and multiple-input-multiple-output-controllers (MIMO) are implemented and evaluated using the model. Furthermore, strongly modified versions of the model are used as a basis for the modeling of CCS power plants.

A demo version of the presented library is available at www.powerplantsimulation.com.

Acknowledgements

This research project has been supported by the German Federal Ministry for Economic Affairs and Energy (project number 03ET7060) which is greatly acknowledged.

Literatur

[Brunnemann et al. 2012] Brunnemann, J., Gottelt, F., Wellner, K., Renz, A., Thüring, A., Röder, V., Hasenbein, C., Schulze, C., Schmitz, G, Eiden, J: *"Status of ClaRaCCS: Modelling and Simulation of Coal-Fired Power Plants with CO_2 capture"*, 9th Modelica Conference, München, 2012.

[DIN 12952] DIN EN 12952-3:2011: *„Wasserrohrkessel und Anlagenkomponenten – Teil 3: Konstruktion und Berechnung für drucktragende Kesselteile"*, Deutsche Fassung EN 12952-3:2011.

[Gottelt et al. 2012] Gottelt, F., Wellner, K., Roeder, V., Brunnemann, J., Schmitz, G., Kather, A.: *"A Unified Control Scheme for Coal-Fired Power Plants with Integrated Post Combustion CO_2 Capture"* Proceedings of the In 8th IFAC Conference on Power Plant Power System Control, Toulouse, Frankreich, 2012.

[Koltermann et al. 2018] Koltermann, J., Meinke, S., Prause, H., Hübel, M., Hassel, E., *„Bewertung der dynamischen Fahrweise eines Braunkohlekraftwerkes mithilfe von zeitlich hochaufgelösten Messdaten und eines instationären Prozessmodells"*, 50. Kraftwerkstechnisches Kolloquium 2018, Dresden.

[Lens 2014] Lens, J.: *„Optimierung des Anfahrvorgangs eines Steinkohlekraftwerks, in Kraftwerkstechnik 2014: Strategien, Anlagentechnik und Betrieb"*, [Beiträge des 46. Kraftwerkstechnischen Kolloquiums am 14. und 15. Oktober 2014 in Dresden], 2014.

[Richter et al. 2019] Richter, M., Oeljeklaus, G., Görner, K.: *"Improving the load flexibility of coal-fired power plants by the integration of a thermal energy storage"*, Applied Energy, Volume 236, 15 February 2019, Pages 607-621.

[Schulze 2014] Schulze, C.: *"A Contribution to Numerically Efficient Modelling of Thermodynamic Systems"*, PhD thesis, Technische Universität Braunschweig, 2014.

[Vojacek et al. 2019] Vojacek, A., Dostal, V., Gottelt, F., Rohde, M., Melichar, T.: *"Performance Test of the Air-Cooled Finned-Tube Supercritical CO_2 Sink Heat Exchanger"*, ASME. Journal of Thermal Science and Engineering Applications, 2019,11(3):031014-031014-11. doi:10.1115/1.4041686.


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