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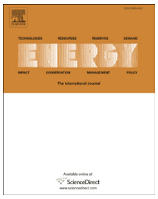

Modelling and transient simulation of a supercritical coal-fired power plant: Dynamic response to extended secondary control power output

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ABSTRACT

Conventional generation units are subject to a changing economic environment and have to adjust their role for modern society's power generation. With substantial amounts of renewable energy production encountering the markets, thermal power plants are facing an increased need for flexible operation and decreasing revenues from selling electricity. Technical adaptations are necessary, though have to be redeemed within very short time spans to secure the plant's profitability. Dynamic simulation in this context serves as a helping tool to evaluate technical improvements and is an established tool in industry as well as in research institutes. This paper focuses on the detailed modelling of a hard coal-fired power plant using the thermohydraulic simulation code Apros. Characteristic of this model is the implementation of the major part of the control system together with the physical model. The comprehensive model enables detailed dynamic simulations with very small error values to process data, as to be seen in the validation. As an application example, the extension of a qualified load jump for secondary control power is realised. The dynamic simulation is thereby used to clarify necessary modifications in the control system and to assess the implications on plant operation.

1. Introduction

1.1. German energy market situation

The strengthening of environmental awareness through political instruments based on a worldwide collaboration has came along with a changeover in the energy production sector in Germany. There, as elsewhere, renewable energies (RE) are used to accelerate the de-carbonisation of the energy production and to contribute meanwhile with a substantial share in the overall feed-in. Supported by the German Renewable Energy Act (EEG) [1], 32.5% of Germany's gross electricity have been produced by RE in the first half-year period of 2015. 64% of those generated through the most relevant sources wind and solar [2]. Following the climate conservation plans of the European Union (EU), the European neighbouring states are subjected to an analogous development with a reduction of CO_2 emissions by 20% by 2020 and an increase of RE share by 20% compared to 1990 [3]. The major challenge connected to the integration of RE in the established energy market lies in the redesign of the role of conventional production sites [4]: Facing increased residual load gradients and a reduced amount of full-load hours [4,5], conventional power plants have to be equipped with technical modifications concerning their flexibility capacities. To ensure a participation in positive revenues through grid services such as control energy supply, and to strengthen their position in the merit order, this holds especially for hard coal and combined-cycle gas and steam turbine power plants (CCGT). Recently decreasing commodity prices in the last months change little to that. Whereas lignite power plants profit from national fuel resources and low carbon certificate prices limiting their variable costs and support their position in the merit order [6]. Therefore, operating companies examine various possibilities to secure the remaining income of their hard coal plant sites. Besides the conclusion of long term OTC-contracts, hedging against price volatility risks, one possibility is the generation of additional income through control energy delivery.

To evaluate consequences of changed operation schemes and technical changes to components, the use of dynamic simulation models is widely spread. During the last years, a variety of simulation tools were further developed and successfully applied to the modelling of conventional power plants, including hard coal and

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Nomenclature

F	friction term
g	gravitational acceleration
h	enthalpy, kJ/kg
k	heat transfer coefficient, $W/(m^2K)$
$\dot{m}$	mass flow rate, kg/s
p	pressure, bar
$\dot{q}$	heat flow rate, W/kg
T	temperature, °C
t	time, s
u	velocity, m/s
z	coordinate direction

Greek symbols

α	volume fraction
β	weighting factor
Γ	mass transfer term
η	efficiency
ρ	density

Subscripts and superscripts

el	electric
g	gaseous
int	interfacial
k	Phase
l	liquid
sat	saturated

Abbreviations

Apros	Advanced Process Simulation Environment
CCGT	combined-cycle gas and steam turbine power plants
DCS	distributed control system
EEG	Erneuerbare Energien Gesetz (German Renewable Energy Act)
EU	European Union
FW	feed water
HP	high pressure
HRSG	heat recovery steam generator
MCR	minute control reserve
IC	injection cooler
IP	intermediate pressure
LHV	lower heating value
OTC	over-the-counter
PCR	primary control reserve
RE	renewable energy
RH	reheater
SCR	secondary control reserve
SG	steam generator
SH	superheater
SP	set point
TSO	transmission system operator

CCGT. Alobaid et al. [7] used Aspen Plus Dynamics to run a numerical study for start-up procedures of a heat recovery steam generator (HRSG). The results support conclusions, found in a former study, which focused on the investigation of a CCGT unit implemented in the commercial simulation software Advanced Process Simulation Environment (Apros) [8,9]. Fast load changes, required through the Great Britain Grid Code have been examined by Zindler et al. [10], investigating the thermal storage capacity of a once-through hard coal vessel in the dynamic simulation program Enipro. Hübel et al. [11] developed a detailed lignite power plant model in Modelica, focussing on primary control reserves and calculation of lifetime consumption. Studies connected to changed operation schemes for coal power plants with increased flexibility requirements often focus on the lifetime consumption of components and adherence or enhancement of temperature and load gradients [12,13]. Start-up analyses of Alobaid et al. [9] examine the dynamic behaviour of a subcritical Benson HRSG for different start-up procedures and developed detailed feed water (FW) and pressure control circuits for the implemented model. On this basis, the high pressure circuit of the Benson HRSG was replaced by a natural circulation loop and subjected to similar start-up procedures in the pursuing work of Mertens et al. [14]. Richter et al. [15] used the dynamic modelling of a coal-fired power plant with a reduced control system in Modelica to evaluate the integration of additional heat storages and the variation of possible load gradients. Since the evaluation of effects on components caused by a changed load regime is more to the results of meeting an external need, another way of employment of dynamic simulation is the prediction of plant behaviour through modified components based on simulation results. Based on tested modifications in the simulation model, the transfer of modifications to the real plant is closely related to the daily operation of the plant. The work of Marusić et al. [16] shows a successful example of an approach in this vein, targeting to a control system modification based on the investigation of an in-house model of a 210 MWel coal-fired Benson vessel. Considering all uncertainties occurring while data collection, model implementation, validation and transfer of results, this approach imposes a high standard of model accuracy. Time-variant influences to the real plant behaviour such as fuel changes and mill degradation come on top.

In the course of this paper, a dynamic hard coal power plant model following a behaviour predictive approach, implemented in Apros 6, is presented. The simulation model is comprehensive through the implementation of all relevant thermohydraulic and time-dependent components together with an extensive control system (Section 3). The model scope is enlarged in comparison to the ones used as basis for the aforementioned publications and is therefore able to serve not only as a reference model in scientific assignments, but also as a user-friendly application in engineering. Purpose of the model is the ability to show sophisticated operation modes such as control energy delivery and make change decisions for the real counterpart based on simulation results. With the possibility of planning required distributed control system (DCS) changes and appropriate relevant controllers‘ parameter settings, the model is intended to deliver a measurable economic benefit for the operator. In a generally unfavourable economic situation, the possibility to accelerate conversion measures is advantageous to extensive site tests. Furthermore, the pursued purpose of providing control energy is to back up the site‘s financial situation. To meet this goal, a structured model validation was conducted in a stationary and dynamic manner, considering both model parts in separate and combination (Section 4). Necessary changes to increase the approved load range for delivery of secondary control reserve are mainly focussing on control system adaptations. These are explained and the resulting model and plant behaviours are shown (Section 5). The main findings of the conducted work are the identification of control system changes and the ability to serve as a reference in site tests, which finally led to a positive prequalification of the real counterpart of the model for an extended secondary control reserve provision.