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Modelling and simulation of a coal-fired power plant for start-up optimisation

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HIGHLIGHTS

- Development of a dynamic power plant model with an innovative level of detail.
- Comprehensive implementation of coal-fired power plant system model.
- New combination of thermodynamic analysis, control structures and stress calculation.
- Focussing on start-up restrictions of coal-fired power plants.
- Virtual environment to test advanced optimisation approaches.

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ABSTRACT

The increased impact from fluctuating energy sources like wind and photovoltaics significantly affects the operational regime of conventional power plants. In the near future, even former base load power plants such as the large-scale lignite plants in Germany will need to start and shut down to balance the electricity system. As frequent starts were not in the focus of optimisation in the past, an extensive potential can be expected to reduce start-up costs and environmental impacts. In order to investigate such optimisation potentials, a comprehensive dynamic simulation model has been developed including process components such as boiler and water-steam cycle but also the power plants control system along with start-up sequence control. After successfully reproducing a reference start of the power plant, the model has been used to identify restrictions for faster start-ups, less fuel consumption and less emission while keeping the thermal and mechanical stress, caused by higher ramp rates, within acceptable bounds.

1. Introduction

In order to save valuable resources and to prevent climate change, an increasing amount of electricity in Germany is produced by renewable sources such as wind and photovoltaics. Due to the intermittent character of those renewable energy sources in combination with a specific demand by electricity consumers, the shape of the residual load is changing rapidly. Since storage capacities for large amounts of electricity are not yet available at economic conditions, coal-fired power plants will play a major role for the next decades. A recent study funded by the German Federal Ministry for Economic Affairs and Energy [1] revealed, that despite Germanys ambitious plans to increase the share of electricity production by renewables towards 50% in 2030, the share of electricity produced by lignite power plants will be in the order of 25% in the same year. Even long-term scenarios like [2] show a high significance of coal and especially lignite-fired power plants until 2050. Due to the increasing penetration of renewable energy, the operational regime of lignite-fired power plants will change significantly. Heimann et al. [3] predicts an increase in the number of start-ups for lignite fired power plants in Germany within the near future, i.e. also formally baseload plants will suffer more than 50 starts per year.

This industry prognosis is in agreement with different academic studies about energy systems with an increasing share of wind energy. Bouwers et al. [4] also calculates scenarios with up to 53 starts for coal

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Nomenclature

α	heat-transfer coefficient
α_t	thermal notch factor
α_{cy}	cylindrical notch factor
α_{sp}	spheric notch factor
δ	wall thickness
ϵ	emissivity
λ	thermal conductivity
Φ_f	shape factor
Φ_{WS}	material factor
ρ	density
σ	stress
ζ	pressure loss coefficient
d_{ms}	base body diameter
e_{ms}	base body wall thickness
(N) MPC	(Nonlinear) Model Predictive Controller
b	Runge-Kutta coefficients
BP	bypass
C	heat capacity
c	velocity
DCS	Distributed Control System
E	energy
f	frequency
g	gravity acceleration
h	enthalpy
u	increment
HP	high pressure
I	inertia
i,j,k	count variables
IP	Intermediate Pressure
k	Runge-Kutta coefficients
LCF	Low Cycle Fatigue
LHV	Lower Heating Value
LP	Low Pressure
m	mass
n	rotational speed
p	pressure
PI(D)	Proportional Integral (Differential)
Q	heat
R	resistance
r	radius
T	temperature
t	time
U	internal energy
UKF	Unscented Kalman Filter
W_t	technical work
X	composition
x	variable
z	height

fired plants in the Netherlands. As the number of start-ups is believed to increase, the importance of optimising this process is becoming more relevant, as [5] points out. Also [6] states that increasing the flexibility of power plants plays a major role in conserving primary energy and reducing CO_2 emissions in a system with increasing penetration from fluctuating renewable energy sources.

Important criteria for start-up optimisation are time, fuel demand and lifetime consumption of the thermally stressed power plant components. For large-scale power plants, security of supply is crucial, testing and implementing changes should be thoroughly prepared. Development of dynamic simulation models is assumed an efficient alternative to field testing, providing a virtual environment to develop and test optimisation strategies. Alobaid [7] gives a wide overview on recent developments on this field. Benato et al. has published a model to predict the dynamic behaviour of a heat recovery steam generator of a gas-fired power plant [8] and a method to predict lifetime reduction of critical components [9]. There have also been ambitions to model coal-fired plants, at least for normal and low load operation as [10–12] have shown. Such models can be used not only to investigate the dynamics but also to optimise control design, as [13,14] have shown. In contrast to standard operation, investigating start-up is more challenging from a modelling point of view. Recent publications about power plant start-up modelling and simulation mainly focus on combined cycle gas power plants as [15] has shown in the modelling environment of *Modelica*, whereas [16,17] have used and compared the modelling environments of *Apros* and *Aspen Plus Dynamics*. As Taler et al. has shown in his studies on the determination of start-up curves [18] and optimisation of boiler start-up, taking into account thermal stresses for coal-fired power plants [19], temperature and pressure differences during start-up are widely believed to be the main limitations for faster and more efficient start-ups. In the current investigations it was found that although thermal and mechanical stress are certainly of interest for optimising start-ups, many limitations in existing power plants result from its process or control system that are currently not addressed in literature. The presented work therefore focusses on the development of an innovative power plant system model and describes effects that need to be considered in the process model as well as in the control system to reproduce a realistic start of an example large-scale lignite plant. The example plant represents a class of typical German lignite-fired blocks that have been built within the 1980s. The blocks include subcritical forced circulation boilers with nominal livesteam pressures of 150–170 bar, and nominal live and reheat steam temperatures ranging from 520 to 545 °C. The nominal power output is about 500 MW, electrical efficiency is about 37%.

The presented paper includes a description of the power plants start-up process, followed by a detailed description of the modelling approach in Section 3. The model is used to compare the actual start-up procedure to the best possible start-up with the currently implemented process and control configuration. Section 4 presents possible optimisation approaches that can be tested using the developed simulator.

2. Start-up process

The start-up of a large-scale power plant is a very complex and highly automated procedure to bring the plant from its starting position into normal operation. Therefore usually mass flows, pressures and temperatures in the process need to reach well-defined thresholds. In general the start-up process of a coal-fired plant begins by achieving the necessary preconditions for the following steps, i.e. preparing auxiliary systems like oil burners, cooling oil circuits, auxiliary steam but also purging the boiler with clean air. In the next step, the oil burners are started sequentially based on certain boundary conditions. As the boiler is heated up, the water starts to evaporate, temperatures and pressures are increasing. At the beginning of the process, the steam does not fulfil the required temperature and pressure conditions to be expanded in the steam turbine. Therefore, it is bypassed until the required conditions are reached. The pressure in the boiler and so its steam flow is controlled using turbine bypass valves. After the gas in the boiler is heated up, coal burners take over the firing, replacing the oil burners one after another. The start-up process is finalised when all the oil burners are switched off and the entire steam flow is expanded in the turbine, i.e. the turbine bypass valves are completely closed. Bringing all the involved systems into their operational modes is guided by start-up step-chains in the plants control structure.