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Dynamic modeling, simulation and optimization of a subcritical steam power plant. Part I: Plant model and regulatory control

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ABSTRACT

System-level dynamic models of power plants are valuable tools for the assessment and prediction of plant performance, decisions on the design configuration, and the tuning of operating procedures and control strategies. In this work, the development of an integrated power plant model is presented. This model is validated against steady-state data from a subcritical power plant with reheat and regenerative cycles. The coal-fired power plant model studied has nominal power generation of 605 MW and efficiency of 38.3%. Traditional, regulatory control architectures are incorporated into and tuned with the dynamic power plant model. Dynamic simulation shows that the plant model is stable for sudden changes in coal load, and the controllers are able to maintain the controlled variables at their set points. In this two-part publication, we present the complete workflow of data collection, model development and validation, control tuning, dynamic optimization formulation and solution, and supervisory control architecture for a coal-fired subcritical power plant. Part I focuses on elements of model development and analysis, illustrating the advantages of acausal, object-oriented modeling in power plant simulation. Part II illustrates the use of this model for efficiency optimization under transient part-load operation.

1. Introduction

The main source of energy for electricity generation in power stations is fossil fuels. Coal-fired steam power plants that operate on the principle of the Rankine Cycle serve more than 1/3 of the electricity demand in the U.S. today [1]. However, due to the need to reduce the CO_2 emissions of the power generation sector [2], extensive programs have been initiated in many countries to partially replace the load of fossil fueled power plants with renewable energy resources, such as wind [3], solar [4], biomass [5], hydro [6], geothermal [7] and tidal power [8]. For instance, power generation from renewable energy sources corresponds to ~20.5% of the daily power demand in the state of California [9]. It is estimated that renewable energy sources will meet 30% of power demand in 2025 and 45% of power demand in 2050 [10]. Previous work has shown that an increase in renewable and distributed power generation will impact the performance and operating requirements of power plants. Edmunds et al. [11] showed that the utilization of gas power plants in the British power infrastructure will be relatively low and subject to more intense ramping operations, with increasing variable renewable penetration. The work by Wang et al. [12] illustrated potential grid stability problems in Europe, where higher penetrations of wind and photo-voltaic sources are realized. Self-regulating load control of conventional power plants is critical in the effort to adapt to the increasing penetration rates of variable renewable generation. The work by Eser et al. [13] showed that the high penetration of renewable resources in 2020 will result in a 4–23% increase of periodic start-ups of conventional power plants, and a 63–181% increase of load ramps. Transient operation of conventional power plants will become necessary to balance the grid load. Meanwhile, due to the increasing safety and environmental regulations, as well as the daily fluctuations in electricity demand, power plants will be (and are) subject to frequent load changes or partial shutdowns.

Physics-based power plant models can play a substantial role in the design of steam power plant configurations, performance analysis, design of control strategies, optimization of system operation, and maintenance. Specifically, plant simulators allow operators to test normal, off-design, transient, emergency, and unconventional operating procedures. On a first level, steady-state modeling is commonly used to design and analyze the integrated power plant or its components. For example, Pei et al. [14] simulated oxyfuel combustion at steady state in a 300 MW pulverized coal-fired plant, using Aspen Plus. They studied and optimized the impact of different mixing percentages of O_2/CO_2, on the combustor flue

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gas. Sahin et al. [15] presented gas turbine models of combined cycle power plants for exergo-economic analysis. The size and configuration of power plants were shown to depend mainly on the levelized cost of electricity, exergy efficiency, or total cost of investment. Zare and Hasanzadeh [16] developed a steady state model of a closed Brayton cycle-based solar power plant, showing that efficiency improvements of up to 30% can be achieved by optimizing gas turbine inlet temperature, evaporator temperature, compressor pressure ratio and heliostat field efficiency. Peng et al. [17] presented a steady state model of a 330 MW hybrid solar/coal-fired power plant, which they used for exergy evaluation. Their simulation results indicated that the hybrid power plant has lower exergy destruction than the solar-only thermal power plant. Zhou et al. [18] evaluated power plant efficiency by modeling a 1000 MW dual reheat ultra-supercritical power plant. They showed that a power plant with ten stages of steam extraction has higher efficiency than a equivalent plant with eight stages. Kumar et al. [19] presented steady state models of subcritical (550 MW), supercritical (660 MW) and ultra-supercritical (800 MW) coal-fired power plants. Their analysis showed that increasing the main steam temperature allows reduction of the auxiliary power consumption and coal consumption. Kakaras et al. [20] developed a steady-state model of a 300 MW coal-fired supercritical power plant, to estimate the efficiency and power generation of an oxyfuel lignite-fired power plant. Their analysis showed that the application of oxyfuel CO_2 capture encompasses an efficiency penalty of 8.5%, with the oxyfuel heat exchangers requiring lower boiler investment than conventional coal-fired power plants.

More recent efforts have focused on dynamic simulation to evaluate the transient operation of power plants, the sizing of equipment and control design. In this context, Colonna and Putten [21,22] developed a power plant model in the software SimECS, and the model was validated by comparison with a lab-scale biomass-fired steam cycle power plant operating at steady state and dynamically. Casella et al. [23,24] developed models for the dynamic simulation of Organic Rankine Cycles (ORC) and Integrated Gasification Combined Cycles (IGCC), using the Modelica language [25] and component models from the ThermalPower library [26]. Chen et al. [27] developed a system-level dynamic model of a combined cycle power plant integrated with chemical-looping combustion and the model was validated at steady-state against commercial plant data. Wang et al. [28] presented work on parametric optimization of supercritical coal-fired power plants. They showed that the optimal pressure ratios of reheating streams were 0.15–0.3, and a decrease of 2% in cost of electricity is feasible. Bhambare et al. [29] modeled a natural circulation boiler of a coal-fired thermal power station. They presented open-loop responses of a dynamic model to step changes in operating parameters, with the dynamic simulator showing good agreement with the actual power plant. Starkloff et al. [30] presented a detailed dynamic model of a 750 MW coal-fired power plant and validated the model against steady-state data from a power plant located in Germany. Their dynamic simulation results were consistent with the plant measurements for load changes of ±27.5%. Power plant models in modern simulation environments have also been explored by several power plant providers, such as ABB [31], EDF [32], and Siemens [33]. Dynamic models are noted to enable development of real-time optimization algorithms for power plant efficiency improvement and emissions reduction.

As the variations of power demand or shut-downs become increasingly frequent, plant control requirements become more challenging. Different control designs and architectures are implemented in power plants to keep up with the challenges in infrastructure brought by the need for variable load operation. Research has focused on implementing advanced control strategies in power plants has drawn attention. For instance, Wang et al. [34] proposed a control design for power systems to rapidly increase excitation and decrease the turbine mechanical input when a fault occurs, and enhance transient stability and the regulation of the generator terminal voltage. Pan et al. [35] presented an adaptive proportional and integral controller using only the available information of model states and outputs of model and plant. This controller was used for load–frequency control of power systems without explicit parameters. Ben-Abdennourt et al. [36] presented a power plant nonlinear model with decentralized control strategy for the boiler turbines, and a power stabilizing control scheme for the generator. Alobaid et al. [37,38] presented a control architecture for a combined cycle power plant during warm start-up, based on models developed in software Apros and Aspen Plus Dynamics. They showed that the drum levels and the feedwater mass flow rate can be simulated and controlled with higher accuracy, than the mass flow rate, temperature and pressure of steam. Overall, research so far has focused on stability and efficiency improvements through advanced control.

Given that subcritical power plants are the most common configuration and will remain so in the next decades, research on the dynamic simulation, optimization and control of subcritical power plants is of interest. Despite significant progress in the dynamic simulation of novel thermal power plants [39], only few dynamic models of coal-fired power plants have been presented in the open literature. Moreover, these models are not available publicly, for researchers to use then as testbeds for further analysis. In this work, a high-fidelity dynamic model with minimum boundary parameterization was developed on the basis of a 605 MW coal-fired, subcritical-pressure, power plant with regenerative reheat cycle. The model was validated against steady-state data from a fossil-fueled power plant reported in the literature [40]. Conventional regulatory controllers were incorporated in the plant model, and the control tuning is discussed. The responses of the most important performance and stability variables during transient load operation are presented. In Section 2, the configuration, design and control architecture of the power plant studied are presented. In Section 3, the development of the plant model is discussed, and all the relevant plant input data and parameters are provided. In Section 4, the validation of the model, quantitatively at steady state and qualitatively in dynamic operation is presented. All the model parameters are provided in Appendix A and the entire power plant model is available in the Supporting Information of this paper.

2. Configuration of the fossil-fueled subcritical power plant studied

A simple diagram of the fossil fuel-fired subcritical power plant simulated in this work is shown in Fig. 1 [40]. The simulated plant corresponds to a 605 MW fossil-fueled reheat cycle designed for nominal turbine conditions of 174 bar and 538 °C steam. Operating conditions for this plant at full load and steady state were reported by Singer [40]. Accordingly, this plant was first simulated with mass flows corresponding to full-load operation. In the plant described in detail in Singer [40], fossil fuel is burnt in the combustor to produce hot flue gas. As shown in Fig. 1, the heat of the flue gas is used to convert the feedwater to high temperature dry steam, through a series of heat exchange steps in the boiler, including the Economizer, Evaporator and Reheater, and Superheater steps. The superheated steam produced in the boiler is expanded in high-pressure (HP), intermediate-pressure (IP), and low-pressure (LP) turbines connected to a generator to produce electricity. Four feedwater heat exchange steps, including a deaerator and three heat exchangers, are supplied with steam streams