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.

Keywords: Power plants, control design, dynamic simulation

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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 CO₂ 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 $\sim 20.5\%$ 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 strate-

gies, optimization of system operation, and maintenance. Specifically, plant
 30 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 compo-
 nents. For example, Pei et al. [14] simulated oxyfuel combustion at steady state
 35 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 com-
 bustor flue 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
 40 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
 45 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
 50 steam extraction has higher efficiency than a equivalent plant with eight stages.
 Kumar et al. [19] presented steady state models of subcritical (550 MW), su-
 percritical (660 MW) and ultra-supercritical (800 MW) coal-fired power plants.
 Their analysis showed that increasing the main steam temperature allows reduc-
 tion of the auxiliary power consumption and coal consumption. Kakaras et al.
 55 [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.

60 More recent efforts have focused on dynamic simulation to evaluate the tran-

sient 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 dynam-
65 ically. 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 com-
70 bustion and the model was validated at steady-state against commercial plant data. Wang et al. [28] presented work on parametric optimization of super-critical 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
75 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
80 in Germany. Their dynamic simulation results were consistent with the plant measurements for load changes of $\pm 27.5\%$. 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
85 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. Re-
90 search 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
95 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.
100 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
105 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
110 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
115 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
120 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 the Appendix 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 Figure 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 Figure 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 extracted from the multi-stage turbines. Three pumps are used for circulating the water after being condensed in the condenser. The preheated condensate re-enters the boiler at high pressure and closes the loop. A reheat cycle is used to reduce the irreversibility of the process, by increasing the turbine inlet temperature and reheating the working steam after expansion in the turbines. The two main sections of this plant, boiler and steam side are discussed in detail in the following.

Figure 1: The reheat, regenerative-cycle, 605 MW subcritical-pressure fossil power plant studied in this work [40].

2.1. Boiler

The boiler converts the feedwater to superheated steam and reheats the steam after expansion in the high-pressure turbine. As shown in Figure 2, the subcritical-pressure boiler is composed of the following subsystems: Drum, Downcomer, Economizer, Evaporator, Reheater, and Superheater. Compared to other types of water tube boilers, the steam drum boiler studied in this work has better tolerance to impurities and lower internal consumption of electricity [41, 42]. The water and flue gas flow paths in the boiler are shown in Figure 2, where the blue solid line denotes the water cycle, and the red dashed line denotes the flue gas stream. In the boiler, two interacting fluid circuits exchange heat; namely, the flue gas circuit and the water circuit. The flue gas circuit starts with the oxidation of fossil fuel with air in the combustor. The combustion gas flows through the Evaporator, Superheater, Reheater and Economizer, successively. In these heat exchange steps, the heat of the flue gas is transferred to the water circuit coils. In the water circuit, the high-pressure feedwater first flows through the Economizer and gets preheated to a temperature 15-30°C lower than its boiling point [42]. The preheated feedwater is collected in a steam drum and then flows to the Evaporator via the Downcomer. The Downcomer

is a set of pipes situated outside the furnace to prevent the water exiting the Drum from evaporating and provide the driving force for natural circulation. The water is partially converted to steam in the Evaporator tubes and the liquid-vapor mixture returns to the Drum. The subcritical-pressure drum separates the steam from the mixture and reduces its moisture. To increase the temperature, reduce the moisture and improve thermal efficiency, the steam flows to the Superheater, exploiting the heat of the flue gas. The Reheater is used to protect the subsequent turbines from being damaged by excessive moisture, by re-superheating the steam after being expanded in the HP turbine [40].

Figure 2: Simplified diagram of the boiler system of the 605 MW subcritical-pressure coal-fired power plant studied in this work.

2.2. Steam side

The steam cycle converts the heat of the hot and high-pressure steam to mechanical power and electricity, and pressurizes the preheat condensate. A simplified diagram of the thermal cycle of the power plant studied is shown in Figure 3. The high-pressure, dry steam produced in the boiler is expanded through multi-stage turbines connected to an electric generator. In the multi-stage expansion process, the steam heat is converted to mechanical torque. After being expanded in the HP turbine, the steam is re-superheated in the boiler to improve plant efficiency. The steam exiting the LP turbine is condensed to liquid in the condenser, fed with cooling water. The condensate is preheated

by the heat of the steam extracted from the turbines in the feedwater heat exchangers, before entering the boiler. A deaerator heater is used to remove oxygen and other dissolved gases from the feedwater. This regenerative heating process transfers heat from one part of the cycle to another to reduce external
190 irreversibility. Three pumps are used to drive the condensate through four heat exchangers. The condensate pump (CP) pressurizes the condensate through the 1st heat exchanger and deaerator (2nd heat exchanger). The CP drives the condensate through the 3rd and 4th heat exchangers. Finally, the boiler feed pump (BPF) pressurizes the condensate back to the boiler to close the loop.

Figure 3: Simplified diagram of the steam side system of the 605 MW subcritical-pressure coal-fired power plant studied in this work.

195 2.3. Control structure

In order to maintain power plant stability and regulate the power plant, necessary consideration was taken for the inclusion of regulatory control loops in the plant. In the plant description by Singer [40], only the open-loop configuration is presented (for design analyses). Therefore, common power plant
200 control configurations [43, 44] were used in this work, which enabled the study of the closed-loop performance of the plant, as well as the analysis of benefits of supervisory control (based on set-point optimization) presented in Part II of this work [45]. Basic control logic to serve the requirements for dynamic per-

formance and stability at varying control loads was incorporated in the power
205 plant in the form of regulatory controllers, tuned to match information available
about the reference power plant. This regulatory control architecture included
controllers for coal and air mass flow rates, pump speeds and valve openings,
and is discussed in detail in the following.

For the boiler subsystem, the regulatory control structure includes Proportional - Integral - Derivative (PID) controllers for the Drum level and steam
210 temperature control, as shown in Figure 4. The Drum level controller manipulates the speed of BFP to keep the liquid level of the Drum at half height, by adjusting the mass flow of the feedwater to the Economizer. The Drum level is measured with a level sensor and the set point was set to 0 m with the
215 actuator being the speed of the BFP. A reverse action controller was used for the superheated steam temperature (T_{SH}) control, using spray attemperators. This tunes the mass flow of feedwater that is mixed with the superheated steam by manipulating the feedwater valve opening, to control the temperature of the steam exiting the Superheater at 538°C. For the temperature controller, the
220 measurement is T_{SH} , the set point is 538°C, and the actuator is the opening of the feedwater valve, as shown in Figure 4. In the combustor, the controller of the air mass flow rate was used to regulate the excess oxygen to ensure near-complete combustion. The control architecture measures the mass fraction of oxygen in the flue gas exiting the boiler, with set point at 3%, and manipulates
225 the mass flow rate, as shown in Figure 4. The selection of 3% oxygen in the flue gas is in accordance with the excess oxygen conventionally used in steam power plants with air combustion boilers [46].

Figure 4: (a) simplified diagram of the boiler with its control design, (b) drum level controller, (c) superheated steam temperature controller, (d) air mass flow rate controller.

* Same stream, **model parameters of PID controllers as shown in Table 5.

For the steam side subsystem, the control architecture incorporated is shown in Figure 5. The speed of the condensate pump is controlled by the condenser level controller to prevent the condenser from running empty and drive the condensate through the 1st feedwater heat exchanger and deaerator (2nd heat exchanger). In the condenser level control structure, the measurement is the liquid level of the condenser, the set point was set to 0.4 m, and the actuator is the speed of the condenser pump. The speed of the condensate booster pump (CBP) is manipulated with input from the deaerator level controller to keep the liquid in the deaerator at a constant level and drive the condensate through the 3rd and 4th heat exchangers. In the deaerator level controller, the measurement is the liquid level of the deaerator, the set point is 0 m, and the actuator is the speed of the CBP. These controllers were tuned using step responses, as discussed in the following.

Figure 5: (a) simplified diagram of the steam side system with its control design, (b) controller for the condenser level, (c) controller for the deaerator level.

*Model parameters of PID controllers as shown in Table 5.

3. Description of subcritical power plant model

The plant of Figure 1 was simulated with a dynamic power plant model developed in Dymola [47] using the Modelon ThermalPower library [26], as shown in Figure 6. The Modelica language used in Dymola is a non-proprietary, object-oriented, and equation-based language for the modeling of complex physical systems. We chose the Modelica language for this simulation, in particular Dymola, because of its acausal structure and extensive libraries of components relevant to thermal cycles. In the past, the ThermalPower library of Dymola has been used to dynamically simulate ORC [24], IGCC [23], and CC-CLC plants [27]. The reference plant, as described in Section 2, was simulated as an integrated model of boiler and steam side. A comprehensive list of the operating data of the power plant model is provided in the Appendix and the Supporting Information of this document. In the following, the main attributes of the model are discussed, along with the steady-state validation of the model developed.

natural circulation boilers [42]. In this work, a circulation ratio ~ 5 was chosen, with the water circulating through the evaporator set to ~ 2500 kg/s. According to the design of heat exchangers in the boiler [42], the pressure loss of water in the Economizer, Superheater and Reheater was set to 5-10%, less than 10% and $\sim 5\%$, respectively. The coal mass flow rate used in the base-case simulation was 56.38 kg/s. The preheat temperature of incoming air was 200°C and the gas exits the Economizer heat exchangers approximately at 1 bar [49]. Based on data from industrial manufacturers [50, 51, 52] and previous work [53, 48, 40], the configuration and initial inputs of the Drum, Downcomer and Spray Attemper-
 270
 275 prator were specified, as shown in Table 1. The level of water in the Drum is reported as an offset from the half height (positive or negative).

Table 1: Boiler parameters.

Drum			
Internal radius [m]	1	Initial pressure [bar]	180
External radius [m]	1.1	Water initial height [m]	0
Length [m]	15	Wall temperature [$^\circ\text{C}$]	380
Orientation	Horizontal	Water phase	Liquid/vapor
Downcomer		Spray Attemperator	
Height [m]	20	Total Volume [m^3]	0.1
Nominal flow [kg/s]	2500	Nominal flow [kg/s]	490
Nominal pressure [bar]	180	Initial pressure [bar]	180
Nominal temperature [$^\circ\text{C}$]	380	Initial temperature [$^\circ\text{C}$]	380

3.2. Steam side model

The heat of the high-pressure and superheated steam is converted to mechanical work, in the HP, IP and LP turbines, which are connected to a power
 280 generator. For the purpose of steam cycle simulation, each turbine was split into cascade sections [40]. A generator model with a constant efficiency of 0.99 was used for simulating power generation. The power generated by this plant arrangement of steam turbines was 605 MW and the nominal plant efficiency was calculated at 38.3%. The condenser was sized to condense the steam at 0.05

bar and 38°C, as shown in Table 2. The simulated feedwater heat exchangers were closed plate heaters that use the steam extracted from turbines and the condensate, with heat exchange occurring through metal coils. The deaerator heater is a drum that mixes the steam from the turbine extraction points with the condensate to remove air and other dissolved gas. The design configuration parameters and initial inputs were specified according to data from manufacturers [51, 52, 50] and the literature [40, 48, 42], as shown in Table 2. The modeled pumps are positive displacement pumps with ideally controlled speed. The condenser liquid level at the bottom is 0 m (the condenser is empty) and it is positive when the condenser is filled. The deaerator liquid level at a half height is 0 m and is reported as positive and negative offset from that level in the following.

Table 2: Steam side parameters.

Condenser			
Diameter [m]	2	Initial pressure [bar]	0.068
Length [m]	10	Water initial height [m]	0.4
Orientation	Horizontal	Wall temperature [°C]	38.5
Deaerator			
Internal radius [m]	2.5	Initial pressure [bar]	4.4
External radius [m]	2.6	Water initial height [m]	0
Length [m]	10	Wall temperature [°C]	120
Orientation	Horizontal	Water phase	Liquid/vapor

4. Model validation and verification

4.1. Steady-state validation

Table 3 reports the steady-state model of selected flows with the order and notation as presented in Figure 1. The steady-state instance of the plant model was tuned to match the performance of the 605 MW fossil fuel plant reported by Singer [40]. The comparison of the reference power plant data with the corresponding predictions from the plant model is shown in Table 4. The power

of 605 MW generated by the subcritical plant model is in excellent agreement
305 with reference data [40]. The model matches the critical data of the stud-
ied power plant, such as the water flow rate, turbine operating pressures and
temperatures. The net power efficiency of 38.3% is consistent with the average
efficiency of coal-fired subcritical power plants reported in the literature [49, 54].
The condenser operating pressure predicted by the model is slightly lower than
310 that of the plant, because the size of the condenser was not reported in [40].
Figure 7 shows the comparison of the prediction of the integrated plant and
the data reported in the literature [40, 42] in terms of temperature and pres-
sure. Due to the heat transfer between water and flue gas in the boiler, the
water temperature increases from 200°C at the Economizer inlet to 538°C at
315 the Superheater outlet. This heat transfer is accurately captured in the model,
as indicated by the temperature predictions in process points 1-6. The pres-
sure loss in the boiler tubing and piping is also in excellent agreement with the
plant data, shown in process points 1-6 in Figure 7 (b). The expansion of the
high temperature and pressure steam in the HP, IP and LP turbines is accu-
320 rately modeled as shown in process points 6-7 and 8-13 in Figure 7. After the
expansion in the HP turbine, the steam is sent back to the Reheater block in
the boiler and is re-superheated to 538°C, as shown in process points 7-8. The
phase change from steam to liquid in the condenser is predicted to occur at 38°C
and 0.05 bar, shown as process point 13. The compression and preheating in
325 the pumps and feedwater heaters are modeled accurately, as shown in process
points 12-13 and 14-17 of Figure 7, depicting the increase of temperature and
pressure of the condensate. In summary, the proposed model is satisfactory and
reliable in terms of reproducing the reported reference power plant operating
data at full load.

Table 3: Selected streams of the coal-fired subcritical power plant model [40, 42, 49].

Stream No.*	Medium	P [bar]	T [°C]	$\dot{m}$ [kg/s]
1	Water (l)	199	188	502
2	Water (l)	179	324	502
3	Water (l)	180.57	352	502
4	Water (l/g)	179	357	502
5	Water (g)	179	357	502
6	Water (g)	170	538	502
7	Water (g)	45	347.2	502
8	Water (g)	39.35	533.5	502
9	Water (g)	24.67	465.8	27.4
10	Water (g)	12.7	377	14
11	Water (g)	7.94	304.6	462.5
12	Water (g)	4.7	244	16.5
13	Water (g)	1.76	144.7	30
14	Water (g)	0.068	34	396
15	Water (l)	0.068	90.4	396
16	Water (l)	2.3	127.2	502
17	Water (l)	13	153.1	502
18	Water (l)	11	183.5	502
19	Coal (s)	1.01	27	56.38
20	Air (g)	1.01	200	627
21	Flue gas (g)	1.01	2037	683
22	Flue gas (g)	1	270	683

* Stream No. corresponds to the process arrangement and ordering shown in Figure

1.

Table 4: Comparison of reference power plant[40] and plant model.

Subcritical Power plant	Reference plant	Plant model
Fuel	Fossil fuel	Coal
Fuel flow rate [kg/s]	-	56.38
Water flow rate [kg/s]	514.1	502
HP operating pressure [bar]	173.7	170
IP operating pressure [bar]	40.5	39.35
LP operating pressure [bar]	12.1	12.7
HP Temperature [°C]	538	538
IP Temperature [°C]	538	533.5
LP Temperature [°C]	378	377
Condenser pressure [bar]	0.068	0.05
Power [MW]	608	605.4
Net efficiency [%]	-	38.3

Figure 7: Comparison of the prediction of the integrated plant and the data reported in [40, 42] in terms of the system temperature and pressure. (1: Economizer inlet; 2: Economizer outlet; 3: Evaporator inlet; 4: Evaporator outlet; 5: Superheater inlet; 6: Superheater outlet; 7: HP Turbine outlet; 8: Reheater outlet; 9: IP1 Turbine outlet; 10: IP2 Turbine outlet; 11: LP1 Turbine outlet; 12: LP2 Turbine outlet; 13: LP3 Turbine outlet; 14: CP outlet; 15: Deaerator outlet; 16: CBP outlet; 17: 4th feedwater heat exchanger outlet).

4.2. Responses to step changes in coal load and control tuning

As discussed earlier, PID controllers were used to regulate the power system and maintain controlled variables at their set points. The proportional term (K_p), integral (K_i), and derivative term (K_d) of each controller were tuned using the plant model, following standard methods [43, 44, 55]. Specifically, the parameters of all the PID controllers, K_i and K_d were first set to zero and then the value of K_p was increased until the output signal started oscillating. K_p was set to approximately half of that value for a quarter amplitude decay of signal. K_i was tuned by increasing its value until the signal started oscillating around its set point. Then, K_d was increased until the output signal reached and maintained the desired set point in an acceptably short period of time. Table 5 reports the resulting tuning parameters of all the PID controllers incorporated

in the power plant model, K_p , K_i , and K_d . The control set points, minimum and maximum outputs, and initial signal output for each controller, reported in Table 5, were specified according to the literature [40, 42, 48, 55].

Table 5: Model parameters of PID controllers.*

Parameters	PID 1	PID 2	PID 3	PID 4	PID 5
Controlled variables	Drum level	T_{SH} controller	Excess O_2	Condenser level	Deaerator level
Manipulated variables	BFP speed	Valve opening	$\dot{m}_{Air}$	CP speed	CBP speed
Set point	0 m	385 °C	3%	0.4 m	0 m
K_p	0.8	-0.2	-0.1	-4.5	-4.5
K_i	0.005	0.01	0.01	0.005	0.005
K_d	0.01	0.01	0.0025	0.0025	0.0025
Max output	1.5	1	1.5	1.5	1.5
Min output	0.5	0.000001	0.5	0.5	0.5
Initial output	0	0.000001	1	1	1

* BFP: Boiler feed pump; CP: Condensate pump; CBP: Condensate booster pump.

345 For the purpose of analyzing the reliability and stability of the power plant simulator, we estimated its performance in closed-loop operation in response to -5%, -10% and -15% step changes in coal load (the model was originally developed and validated for full load). The set points of controlled variables, T_{SH} , liquid level of Drum, liquid level of condenser and liquid level of the deaerator, and
350 different coal loads are provided in Table 6.

Table 6: Set points of controlled variables and coal loads.

Controlled variable	Set point	Coal load	Coal flow [kg/s]
Drum level [m]	0	100%	56.38
T_{SH} [°C]	538	95%	53.56
Condenser level [m]	0.4	90%	50.74
Deaerator level [m]	0	85%	47.92

Figure 8 presents the response of the controlled variables during different step changes in coal load, specifically the variation of the liquid level of the Drum, T_{SH} , liquid level of the condenser, liquid level of the deaerator, and power generation. The -5%, -10% and -15% step changes in coal load were imposed after 1 hr of simulation and the duration of the change was set to 1 s. The timescale of 1 hr is reasonable and representative of control actions in response to coal load changes in the power plant. It is also used as the time span for supervisory control actions in Part II of this work.[45] The power plant model was first initialized to steady state at full load. As shown in Figure 8, the negative step change in coal flow rate leads to small fluctuations in the controlled variables and a corresponding step change in power generation. For example, in Figure 8(a), the drum level oscillated during the transition to part load operation, but this oscillation was negligible. The controller enables the drum level to return to the set point within minutes. Specifically, the drum level reached steady state in 10 min, 17 min and 20 min after -5%, -10% and -15% step changes in coal load, respectively. Figure 8(d) shows the corresponding power generation for the three different coal load operations, as well as their temporal responses. The power generations was 577 MW, 548 MW and 519 MW at 95%, 90% and 85% coal loads, respectively. The controller tuning was robust for the condenser and deaerator levels with rapid responses and small oscillations. In summary, the model responses to step changes in the coal load illustrate the robustness of the controllers, and the value of the dynamic model of the power plant in tuning the controllers to maintain the regulated variables at set point, even for sudden (and somewhat unrealistic) changes in coal load. This power plant model, validated quantitatively at steady state and qualitatively in terms of closed-loop dynamic performance, can be used as a robust test bed for dynamic simulation and optimization of power plants, which is the focus of Part II of this series [45].

Figure 8: Response of the power plant model with control design to -5%, -10% and -15% step changes in coal load, in terms of (a) T_{SH} , (b) the liquid level of the Drum, (c) the liquid level of the condenser, (d) the liquid level of the deaerator and (e) power generation.

5. Conclusions

380 We presented the development of a 605 MW coal-fueled subcritical pressure power plant model, with reheat and regenerative cycles. The simulation results of the power plant operating at full load were in excellent agreement with data from a reference power plant. The steps for designing and tuning a regulatory control architecture for this power plant were presented in detail. The stability and flexibility of the studied power plant were analyzed with dynamic simulations, performed in response to -5%, -10% and -15% step changes in coal load. 385 The plant model exhibited fast responses to these sudden changes in coal load, showing that the regulatory control scheme was tuned to reliably and robustly keep the controlled variables at their set points and the integrated plant safe and operational. Overall, the system-level model of the power plant with its regulatory control scheme embedded in the model is a robust test bed for dynamic simulation and optimization. In Part II of this work, we focus on the dynamic modeling of power plants in response to time-varying power demand, and the design of a supervisory controller for optimization of the net plant efficiency, 390 with parallel reduction of coal consumption and CO₂ footprint. The model (developed in the equation-oriented environment of Modelica) is available free of charge as a Supporting Information to this paper.

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Appendix: Parameters and fluid media properties used in the power plant model

As mentioned in the main text of this manuscript, the power plant model was developed in the simulation environment of Dymola [47] using the Modelica modeling language [25]. In this section we report all the model parameters necessary to reproduce the model developed. The two phase medium and gas medium used in the Dymola model were the WaterIF97 of the Modelon library and the ExhaustWithAsh medium of the ThermalPower library, respectively. The air medium had nominal mass composition of 1.3% Ar, 75% N₂, 23% O₂ and 0.7% H₂O. The parameters of all of the component models were kept at their default values if not otherwise specified in this section. For the heat exchangers in the boiler, the heat transfer type was set to “Gas side heat transfer over bundles” in the primary (prim) channel with the ExhaustWithAsh medium, and the “Constant overall transfer coefficient” model (α) was used for the secondary (sec) channel with the WaterIF97 medium. In the Evaporator, the radiation-inclusive heat transfer model was used with a total effective heat transfer area of 3023 m² and enhancement factor of 0.12. Table A1 shows the model parameters of the heat exchangers in the boiler. The medium in the steam side subsystem was the WaterIF97 Modelica medium. In the water preheaters, the vapor was set to flow through the primary channel and the liquid phase water through the secondary channel. Table A2 shows the parameters of water preheaters in the steam side. Tables A3 and A4 present the parameters of the steam turbines and pumps, respectively.

Table A1: Model parameters of the heat exchangers in the boiler.

Parameters	Economizer	Evaporator	Superheater	Reheater
Geometry				
Length [m]	5	4.5	5	5
Width [m]	5	4.5	5	5
Height [m]	3.5	3.5	3.5	3.5
Tubes/row	199	160	199	199
Passes	120	160	120	120
Initialization				
$T_{\text{prim,in}}$ [bar]	718	1963	1582	985
$T_{\text{prim,out}}$ [bar]	327	1582	985	718
$P_{\text{sec,in}}$ [°C]	199	184	182	45
$P_{\text{sec,out}}$ [°C]	182	182	173.7	40.5
Correlations				
ΔP_{sec} [bar]	14.5	1.2	6.2	4.5
α [W/(m ² ·K)]	1275	72	158	158

Table A2: Model parameters of the water preheaters in the steam side.

Parameters	1st preheater	3rd preheater	4th preheater
Geometry			
Plates	1200	2600	3000
Plate height[m]	8	8	6
Streams			
α_{prim} [W/(m ² ·K)]	3500	1200	2170
ΔP_{prim} [bar]	1.292	0.2	0.1
$P_{\text{prim,in}}$ [bar]	1.36	12.7	25.2
$\dot{m}_{\text{prim}}$ [kg/s]	27	50	30
$H_{\text{prim,in}}$ [kJ/kg]	2755	680	3300
$H_{\text{prim,out}}$ [kJ/kg]	381	500	747
α_{sec} [W/(m ² ·K)]	3500	6000	15000
ΔP_{sec} [bar]	0.01	0.2	0.2
$P_{\text{prim,in}}$ [bar]	4.4	12.4	12.2
$\dot{m}_{\text{sec}}$ [kg/s]	30	515	515
$H_{\text{sec,in}}$ [kJ/kg]	148	572	600
$H_{\text{sec,out}}$ [kJ/kg]	381	738	625

Table A3: Model parameters of the steam turbines in the steam side.

Parameters	HP	IP1	IP2	LP1	LP2	LP3
$\dot{m}$	514	514	484.4	455.1	430.1	382.9
$\eta_{\text{isentropic}}$	0.85	0.92	0.855	0.883	0.8	0.88
P_{in} [bar]	173.7	40.5	25.2	12.7	4.8	1.2
P_{out} [bar]	45	25.2	12.7	4.8	1.2	0.068
H_{in} [kJ/kg]	3391	3550	3393	3212	2985	2720
H_{out} [kJ/kg]	3063	3394	3212	2985	2730	2480

Table A4: Model parameters of the pumps in the steam side.

Parameters	CP	CBP	BFP
Volume [m ³]	0.1	0.1	001
Flow rate [m ³ /s]	0.4298	0.593	0.629
$\dot{m}$ [kg/s]	429.8	513.9	514
P_{in} [bar]	0.16	3.31	12
P_{in} [bar]	3.31	12.4	199
H_{in} [kJ/kg]	142	625	800

The control tuning was based on standard control tuning methods [43, 44] of PID controllers discussed in the literature [55]. Here, the tuning for the drum level controller is used as an example of the control tuning excessive. Table A5 provides the values of K_p , K_i , and K_d before and after the tuning.

Table A5: K_p , K_i , and K_d for Drum level controller tuning.

Parameters	Pre-tuning	Post-tuning
K_p	0.5	0.8
K_i	0.05	0.005
K_d	0.1	0.01

Figure A1 shows the temporal profile (including initialization) of the level of water in the Drum with the controller before and after tuning. The drum level controller was tuned to enable the controlled variable to reach set point without oscillations and rapidly. This was achieved by increasing K_p from 0.5 to 0.8, and decreasing K_i and K_d from 0.05 to 0.005, and 0.1 to 0.01, respectively.

Figure A1: Drum level controller tuning.

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