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Executive Summary

This report presents the different models developed for the combined cycle start-up application.
A first Modelica model is built with the ThermoPower library. The model is implemented in Dymola. However, this model is too complex to be used in a control law.
Next, a Modelica smooth model is developed. This model is implemented in Dymola and can be used for nonlinear gradient-based optimization.
An interpolated transfer function model is also developed. The local linear models obtained by identification are aggregated thanks to membership functions so as to obtain a wide-range model. This model is implemented in Simulink.
The Modelica smooth and Simulink interpolated models responses are close to the initial model and will be used for HD-MPC synthesis.

1 Introduction

Combined Cycle Power Plants (CCPPs) are complex systems composed by many interacting subsystems that are generally controlled using a classical hierarchical structure, where the upper layer coordinates the local controllers. In the HD-MPC deliverable D.7.1.1, the control specifications for the start-up of a CCPP with HD-MPC have been defined, the plant has been partitioned in subsystems and for each subsystem the operational constraints and the existing control loops were specified. This information has been used to build a model of the process. The CCPP considered in the deliverable D.7.1.1 is a process with a 1-1-1 configuration: one gas turbine (GT), one steam turbine (ST), and one heat recovery steam generator (HRSG) with three levels of pressure (high, intermediate, and low). This type of plant is very complex (high-order nonlinear model), and we decided to focus on a process with the same configuration but with only a single level of pressure (high pressure circuit). The model will be used to simulate the hot start-up sequence of the plant.

The current report presents three CCPP models and the results of the open loop simulations. It is organized in the following way. Chapter 2 describes the developed CCPP model with a single level of pressure. This second chapter also gives information about the model initialization and the results of the validation. The two control models derived from the CCPP model and the validation results are described in Chapter 3. Conclusions and future steps are reported in Chapter 4.

In industrial applications, one of the most important reasons for the limited use of the model predictive control methods, is the significant time and effort necessary to develop and validate process models that are valid over a wide operating range. At the same time, it is very important that these models are suitable for optimization in terms of issues such as complexity, accuracy and smoothness. For the combined cycle power plant application such models which enable to validate the methods for hierarchical and distributed MPC, have been developed.

To realize these types of models, the powerful modeling language Modelica [1], [2], [3], [4], has been used. Modelica is an object-oriented language for modeling of large, complex, and heterogeneous physical systems. The most important features are:

- Object-oriented modeling. This technique gives the possibility to create physical model components, which are employed to support hierarchical structuring, reuse, and evolution of complex models from several different domains.

- Acausal modeling. Modelica is based on equations instead of assignment statements. Direct use of equation gives a better reuse of model components, since components adapt to the data flow context in which they are used.

- Physical modeling. The model components can correspond to real physical objects. The structure of the model is more natural in than the traditional concept based on block-oriented models, which concerns more the computational aspects than user aspects.

The developed CCPP model, is relied on the open Modelica library for the modeling of thermal power plants (ThermoPower [5], [6]), and has been parameterized with design and operating data from a typical unit. The modeling and the simulation have been realized using the Dymola [8] tool. The plant model has the following features:

- It can represent the whole start-up sequence (deliverable D7.1.1);

- It includes a model of thermal stress in some critical components, which is the most limiting factor for the start-up time (deliverable D7.1.1).

- It neglects phenomena and components which are not critical for the start-up sequence, in order to keep the complexity of the model at a reasonable level.

Nevertheless, the complexity of the developed CCPP model is quite high (strongly nonlinear, many discontinuities, steam/water tables, etc.) and makes its use difficult for control purposes, therefore it will be used for simulation and as a reference for realization of more simplified models. For control purposes, two models, a Modelica smooth model (3.1), and a Simulink plant model (3.2) (both derived from the complex CCPP model) have been developed. These two models capture the essential features of the plant and will be used in model based process control applications.

2 CCPP model

2.1 Description

The combined cycle power plant model has been elaborated according to the specifications given in deliverable D.7.1.1 and the Figure 1 represents the structure of CCPP considered, with the main components:

- Gas turbine (GT);
- Heat recovery steam generator (HRSG);
- Steam lines (SL) or the pipes system between HRSG and ST ;
- Condenser;
- Steam turbine (ST).

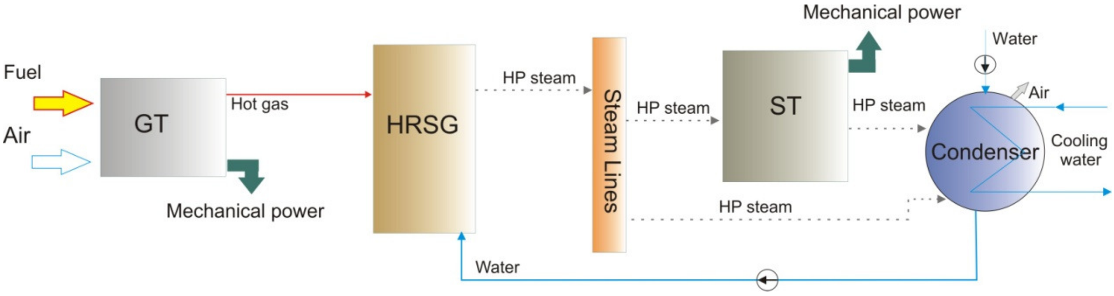


Figure 1: Schematic of a simple CCPP with one level of pressure

Starting from this type of plant with (1-1-1) configuration, a model using Modelica/Dymola, relied on the components from ThermoPower library [7], has been developed. The model represents the evolution of the main plant parameters (pressure, temperature, level), and has been parameterized with real data.

Figure 2 presents the configuration of the CCPP model realized in Dymola, corresponding to the plant structure. The CCPP model is obtained by connecting the models of the GT unit, HRSG unit, SL unit, ST unit and condenser, via thermo-fluid connectors [6]. Details about CCPP model components can be found in Appendix A.

Gas Turbine

Generally, the GT is not a limiting factor for start-up, because the HRSG start-up is much slower than GT start-up time, so for the GT, a simplified model has been used, a model from the ThermoPower library with:

- maximal power of 235 [MW];
- nominal flue gas flow rate of 585.6 [kg/s];
- nominal fuel flow rate of 12.1 [kg/s].

Heat Recovery Steam Generator

The HRSG has a single pressure circuit (high pressure) with:

- nominal HP steam flow rate of 70.6 [kg/s];
- nominal HP steam pressure of 129.6 [bar].

The HP circuit is made using the ThermoPower elements, and has the following components:

- Economizer;
- Steam drum;
- Evaporator;
- Superheater.

The limitations for a faster start-up in this circuit are mainly linked to the material stress and component lifetime consumption (deliverable D.7.1.1) therefore a model of stress is included.

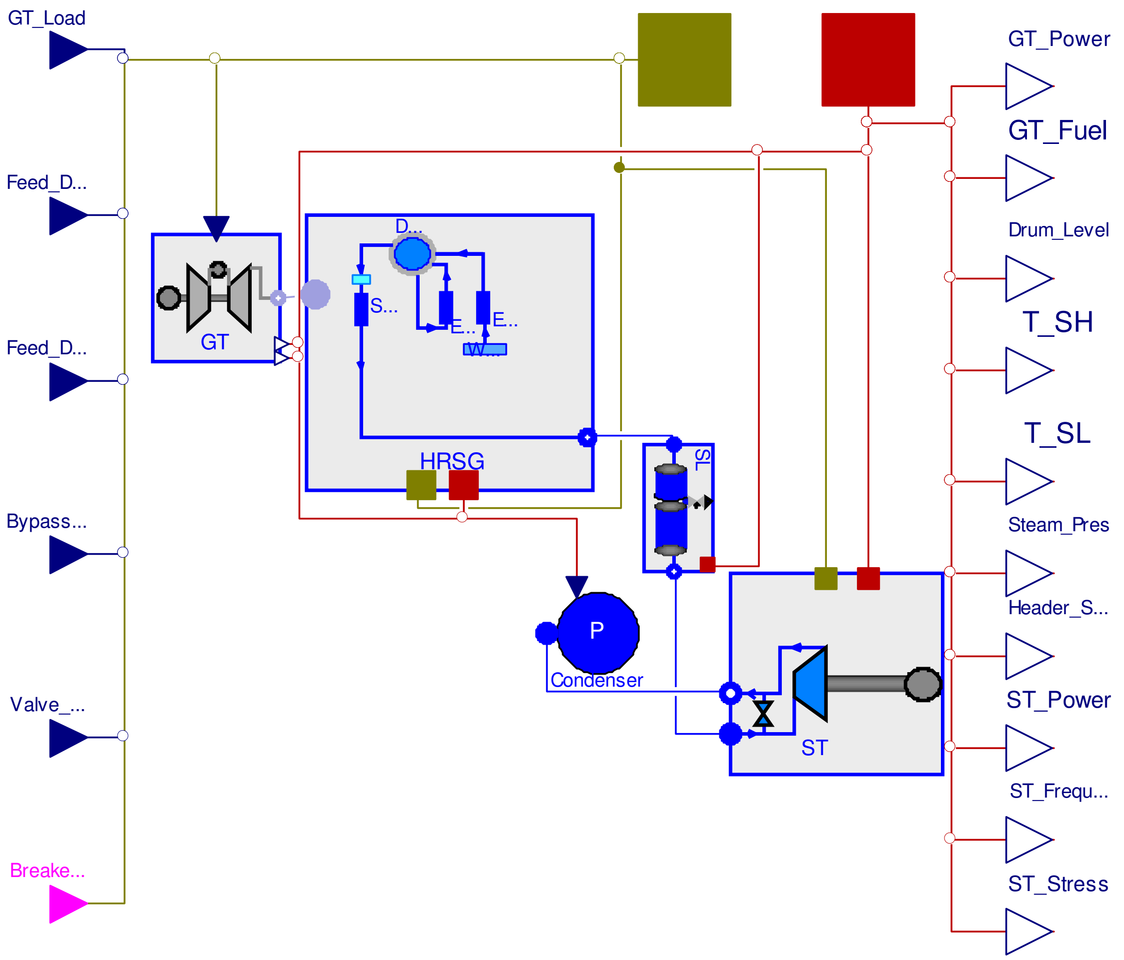


Figure 2: The configuration of Modelica/Dymola plant model

Steam Lines

The system of pipes that makes the connection between HRSG, the ST and the condenser, has a length of 130 [m] and is provided with an evacuation system (to eliminate the condensates).

Steam Turbine

The ST has a single stage (high pressure stage) and the maximal power is of 100 [MW]. The main limitations for a faster start-up are originated in the drastic thermal transients of the turbine components, more precisely, the turbine shaft that is in contact with highest steam temperatures (downstream of the turbine impulse stage). This stage is represented separately and connected to a thermal stress model of the shaft section.

Condenser

The representation of the plant parts that work with low temperature is very simplified, since these are not critical for start-up, therefore the condenser and the feed-water system is represented in a simplified way.

The CCPP model developed has 6 input signals, 10 output signals.

The inputs are:

- GT_Load – the GT load [pu];
- Feed_Drum – the water flow rate that feeds the HRSG circuit [kg/s];
- Feed_DSH – the water flow rate that feeds the desuperheater [kg/s];
- Bypass_ST – the bypass position [pu];
- Valve_ST – the admission valve position of the ST [pu];
- BreakerClosed – the generator grid breaker of the ST [0/1].

The outputs are:

- GT_Power – the GT power [W];
- GT_Fuel – the GT fuel flow [kg/s];

- Drum_Level – the drum level [m];
- T_SH – the steam temperature in the superheater [°C];
- Steam_Press – the steam pressure [bar];
- Header_Stress – the header thermo-mechanical stress [Pa],;
- T_SL – the steam temperature in the SL [°C];
- ST_Power – the ST power [W];
- ST_Frequency – the ST frequency [Hz];
- ST_Stress – the ST rotor thermal stress [Pa].

To show the complexity of the CCPP model some statistics information from Dymola are given:

- The DAE has 2664 scalar unknowns and 2664 scalar equations;
- Number of components: 219;
- Variables: 3416 of which:
  - Constants: 752 (1061 scalars);
  - Parameters: 869 (931 scalars);
  - Unknowns: 1795 (2664 scalars);
- Continuous time states: 53 scalars.

2.2 Initialization – Initial state

The initialization of the plant model in the shut-down state is difficult (insufficient knowledge of the initial values, low or zero flow rates) therefore the Modelica model is initialized near the full-load steady state. The model is brought to a state corresponding to the hot start-up of the plant by a shut-down sequence. Details about this sequence and how to initialize the model can be found in Appendix A.
Following the sequence specified in HD-MPC deliverable D7.1.1, the initial state coincides with the middle of the second stage, *HRSG Start-up phase,* when the GT is synchronized and the HRSG is ready (the temperature condition is fulfilled, that means the superheater metal temperature is greater than steam temperature).

During the first stage (*Preparation phase)* and the first part of the second stage (*HRSG Start-up phase)*, the plant is purged, the GT is started, accelerated and synchronized to the grid, while the HRSG is in the warming mode. This part of the start-up sequence will not be considered since is not critical for the start-up time and can not be improved.

The state corresponding to the hot start-up of the plant is then:

- ST with no steam flow, stopped (“almost “):
  - Temperature distribution of the turbine shaft around 420 [°C];
  - Bypass opening around 0.16;
  - Admission valve completely closed 0;
  - Generator grid breaker 0 (open);
- Steam Line:
  - Metal wall temperature around 306 [°C];
- HRSG:
  - Steam pressure 65 [bar] in the HP circuit;
  - Steam temperature around 305 [°C] in the HP circuit;
  - Water flow rate around 8.9 [kg/s];
  - Water flow rate of the desuperheater 0 [kg/s];
  - Drum level around 0 [m] (the drum is measured with respect to the middle of the drum);
    - *Economizer:*
      - Metal wall temperature around 281 [°C];
    - *Evaporator:*
      - Metal wall temperature around 282 [°C];
    - *Superheater:*
      - Metal wall temperature gas side around 307 [°C];
- GT:
  - GT Power around 17.6 [MW][1];
  - Gas flow rate 454 [kg/s];
  - Gas temperature around 312 [°C].

2.3 Validation & open-loop simulation results

The CCPP model has been designed and parameterized with data from a typical unit and is based on the ThermoPower library, which has been validated against the experimental data. The parameters used in this case study have to be adapted for any real case implementation.

[1] It corresponds to the GT_Load = 0.075

To show the evolution of the main plant parameters, some scenarios have been realized; for all of them the model has been initialized in the hot start-up state and the simulation interval was of 1200 seconds.

Scenario 1

- GT_Load is gradually increased until 0.3 (30% of load). At 300 [s], a ramp of height 0.225 and with duration of 800 s is given on the GT_Load.
- The other inputs (Feed_Drum ≈ 8.9, Feed_DSH=0, Bypass_ST ≈ 0.16, Valve_ST=0, BreakerClosed=0, see Initial state) have been kept constant.

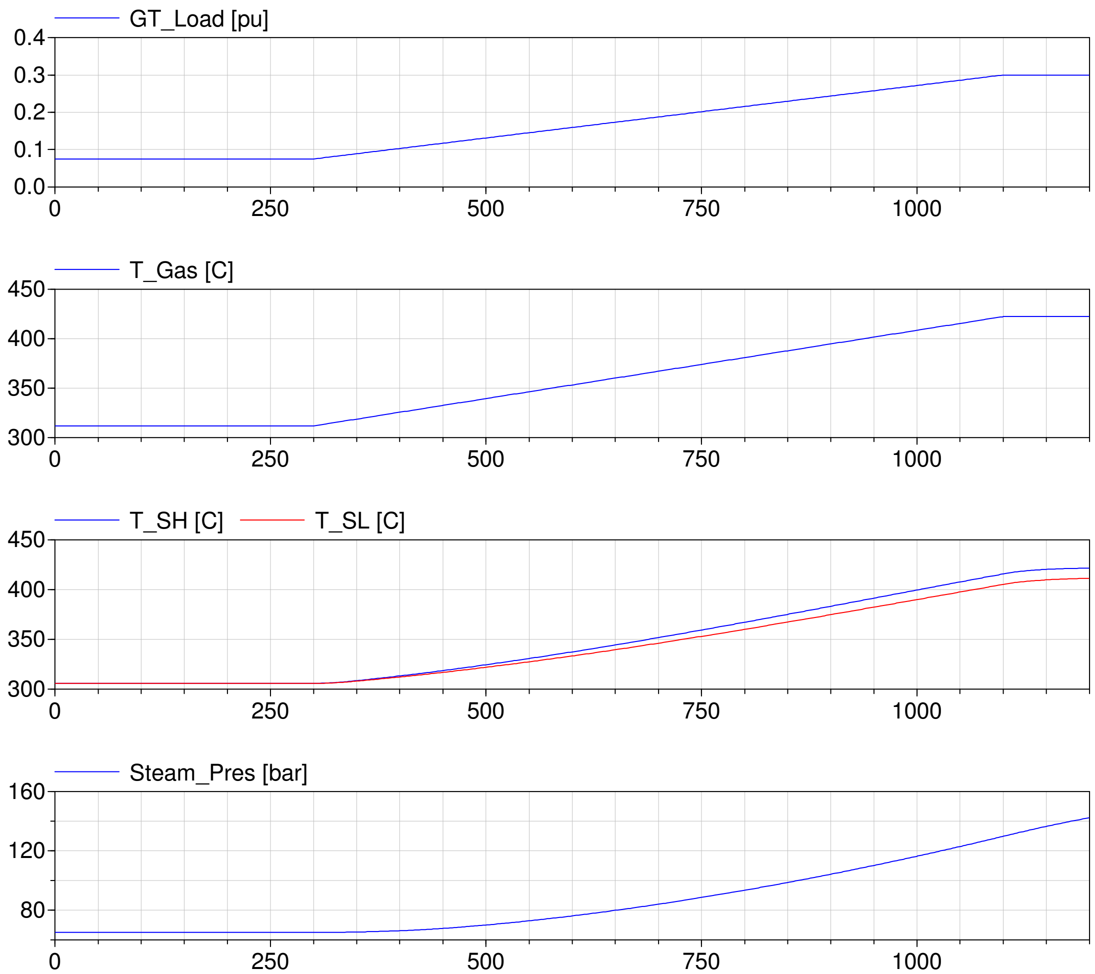


Figure 3: GT load ramp, gas temperature (Gas_T), steam temperature in superheater (T_SH), steam temperature in steam line (T_SL)) and the steam pressure (Steam_Pres)

As shown in Figure 3, the gas temperature increases with the GT load increasing and the steam pressure and steam temperature respectively are related to the gas temperature (steam temperature and pressure go up with the gas temperature).

Scenario 2

- The same assumptions as in the scenario 1 are considered (ramp on the GT_Load), but varying Feed_DSH. At 1000 [s], a step is given on the Feed_DSH.

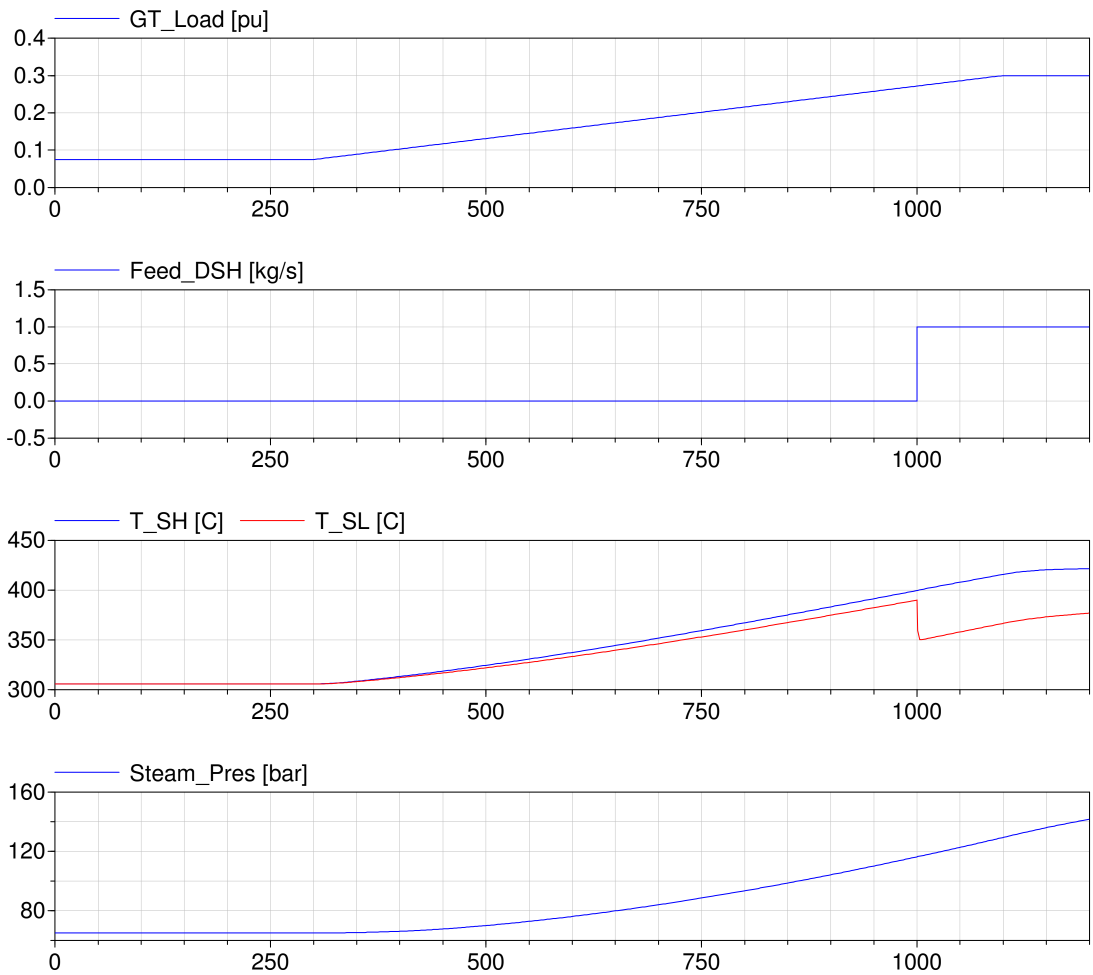


Figure 4: Feed_DSH step, steam temperatures (T_SH - in superheater, T_SL - in steam line) and steam pressure

Figure 4 shows that when the Feed_DSH step is applied the steam temperature in the steam line (T_SL) decreases. The pressure change is insignificant.

Scenario 3

- At 300 [s], a step of height 0.1 is applied on the GT_Load.
- At 1000 [s], a step of height 0.1 is given on the Bypass_ST.
- The other inputs are kept constant.

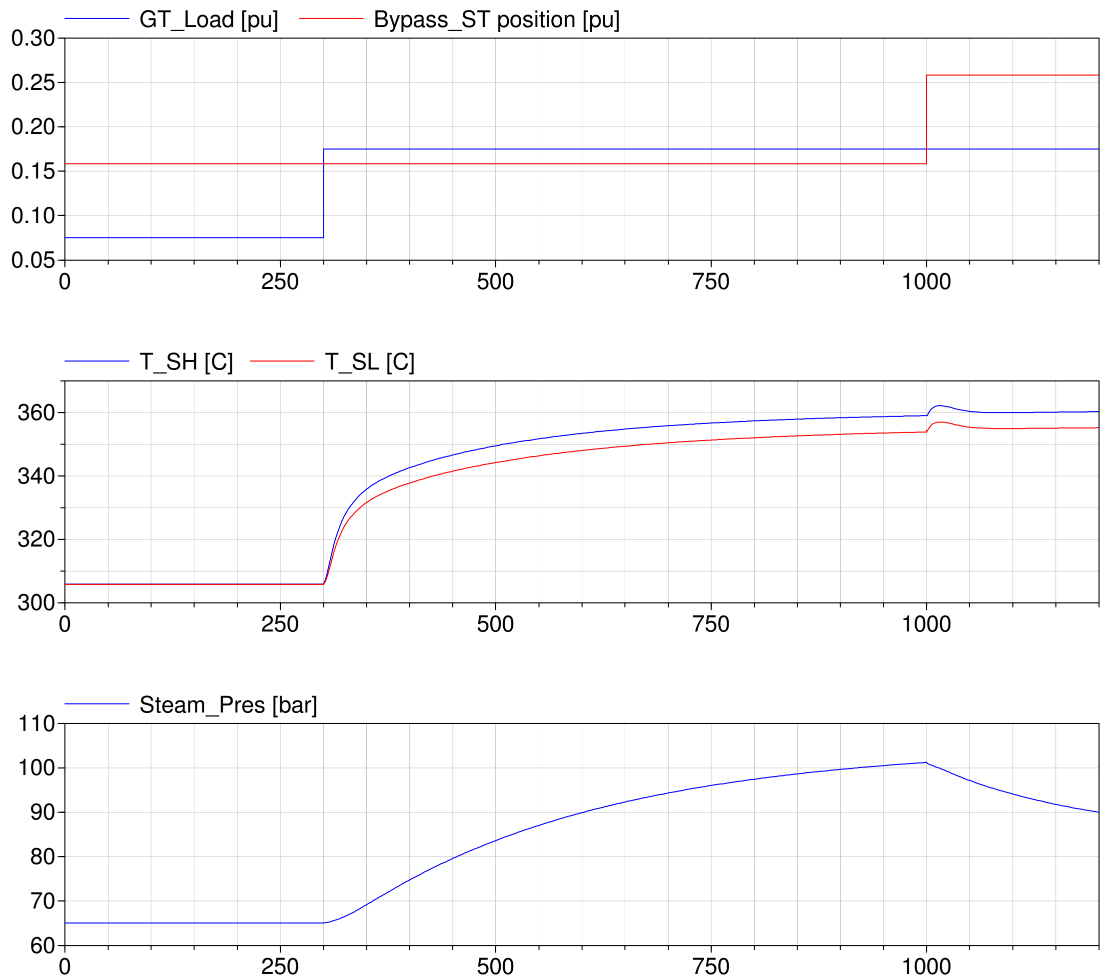


Figure 5: GT_Load step, Bypass_ST step, steam temperatures (T_SH - in superheater, T_SL - in steam line) and steam pressure

From the Figure 5 it can be remarked that the steam temperature increasing is faster thant in the previous scenarios, generated by the GT_Load step and a steam pressure reduction with the bypass opening.

Scenario 4

- At 300 [s], GT_Load is increased until 0.3.
- At 1000 [s], GT_Load is decreased until 0.1.
- The other inputs are kept constant.

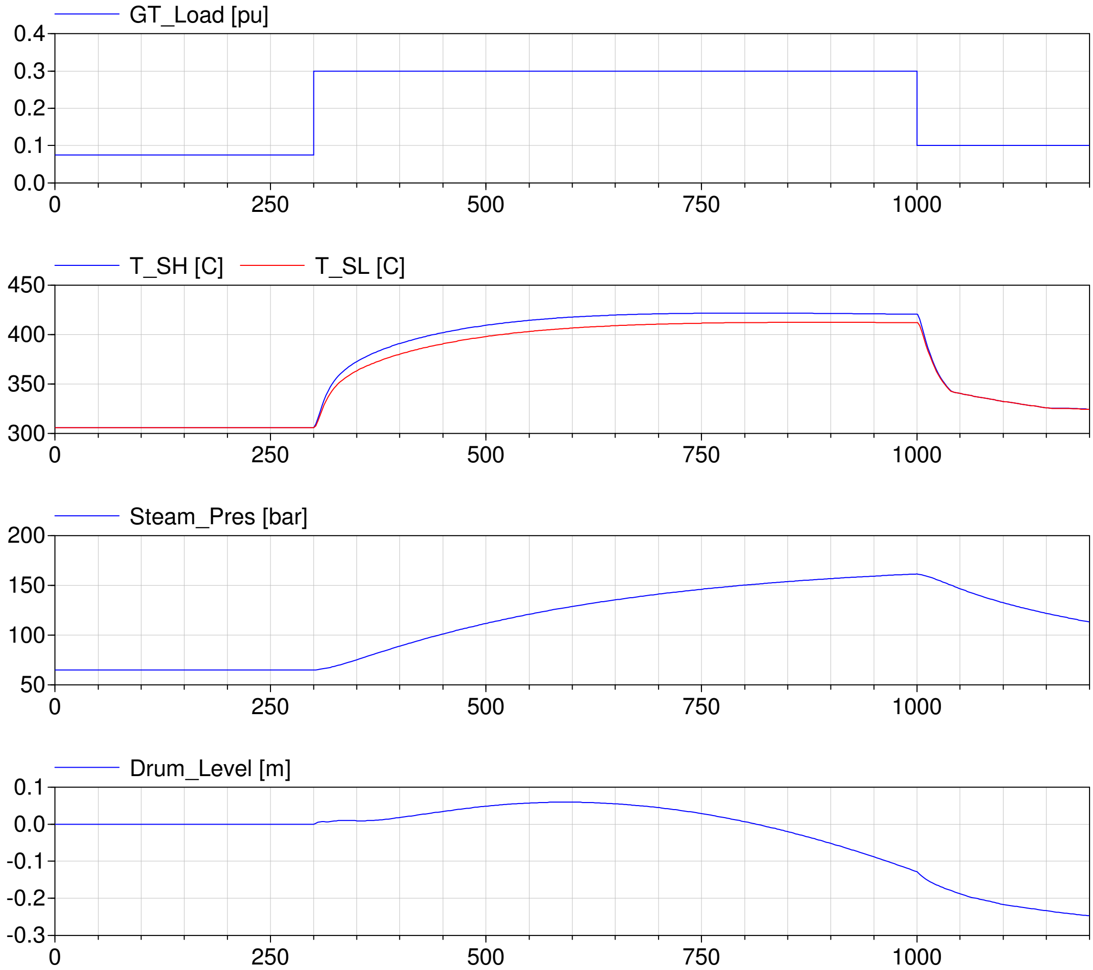


Figure 6: GT_Load steps, steam temperatures (T_SH - in superheater, T_SL - in steam line), steam pressure and drum level

In Figure 6 the swell effect generated by the GT_Load step can be seen; this swell effect is followed by a diminution of drum water level due to the increase of quantity generated steam. It can also be remarked that as soon as the GT_Load decreases, the temperature and pressure of the steam reduce.

Scenario 5

- At 300 [s], a step is applied on the GT_Load (increase until 0.3).
- At 600 [s], a ramp of height 0.2 and with duration 500 [s] is given on the Valve_ST.
- The other inputs are kept constant.

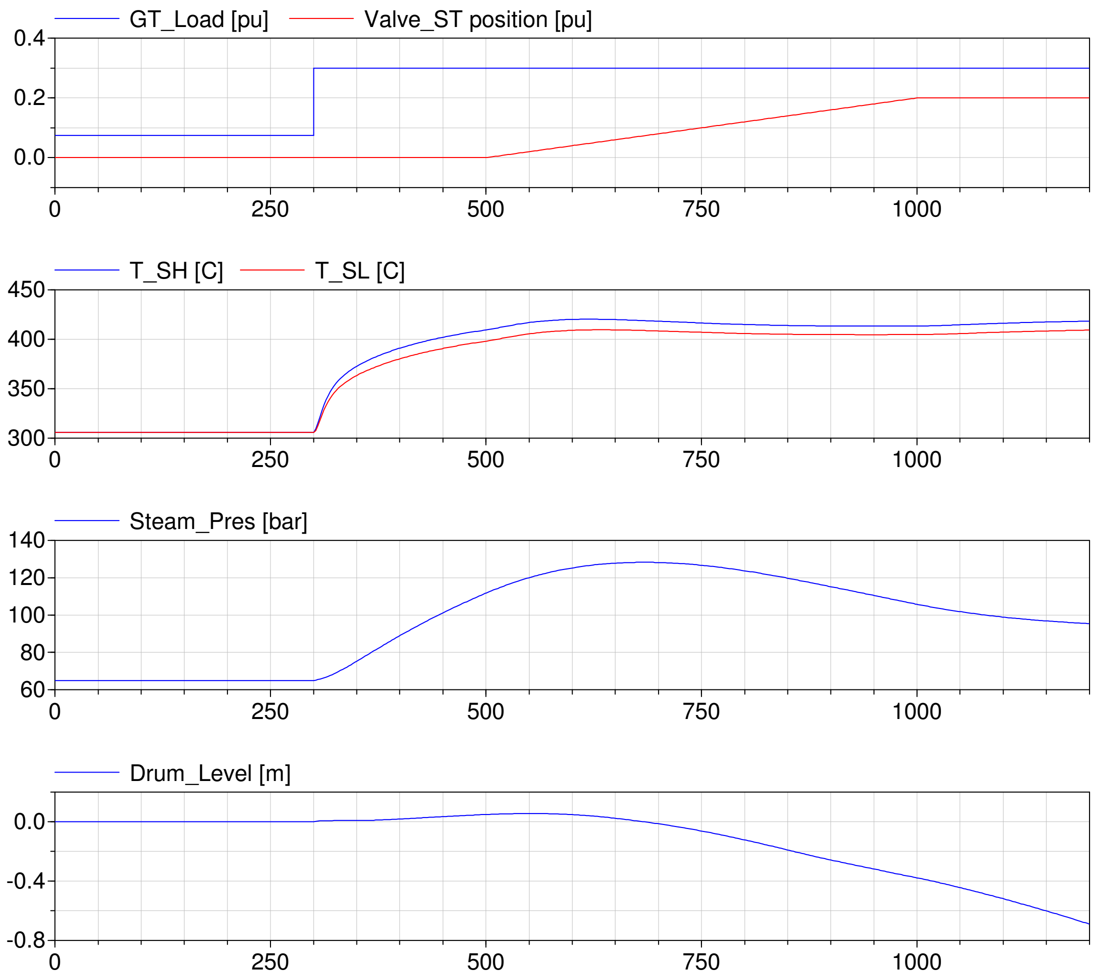


Figure 7: GT_Load, Valve_ST, steam temperatures (T_SH - in the superheater, T_SL - in the steam line), steam pressure and drum level

Figure 7 shows the effect of the admission valve opening namely the reduction of the steam pressure in circuit. It can also be observed a slight diminution of the steam temperature. Relating to the drum level the water decreases faster than in the previous scenario, because the GT Load is kept constant at 30%, until the end of the simulation.

3 Control models

The physical-knowledge-based model developed in Modelica/Dymola is difficult to use for control purposes, due to its complexity (strongly nonlinear model, a lot of discontinuities, steam/water tables, etc.). Other kinds of model are needed to design the control. A first approach is to modify the model components to be suitable for optimization and not re-create new components for a new model. A second approach is to interpolate linear models obtained by identification with data obtained on the complex model. The control models will be compared to the initial more complex one.

3.1 Modelica smooth model for optimization purpose

The use of the modeling language Modelica in model based process control applications has many advantages. With the Modelica a large class of models (linear, nonlinear, hybrid etc.) can be described and for the simulation of these models there are many efficient software tools [8], [9], [10], on the other hand tool support for static and dynamic optimization is generally weak. In terms of the dynamic optimization, the complexity of the Modelica models is a major challenge. There are a few tools used for optimization and control on the market that work together with the Modelica models. Examples are the dynamic optimization software DyOS [11], developed by the Institute for Process Systems Engineering at RWTH Aachen University, another is JModelica [12], an extensible Modelica-based open source platform for optimization, simulation and analysis of complex dynamic systems, also Cybernetica CENIT [13], a software package for NMPC, developed by Cybernetica.

3.1.1 Elaboration of Modelica smooth model

To make a Modelica model ready to be used with these tools, some modifications and compromises are required, but in the same time keeping the model validity over varying operating conditions. For the MPC methods, it is essential to have a reliable model of the plant dynamics and accurate output prediction. Therefore, before starting to develop such models, the task in terms of complexity, accuracy and smoothness must be clearly specified.

The CCPP developed model uses the components from ThermoPower library. The ThermoPower library is an open-source library for the modeling of thermal power plants at the system level, to support the design and validation of control systems. The library has been developed according to following principles:

- The models are derived from the first principle equations or from acknowledged empirical correlations;
- The model interface is totally independent of the modeling assumption adopted for each model, to achieve full modularity;
- The level of detail of the models is flexible;
- The inheritance mechanism is used with limitation, to maximize the code readability and modifiability.

All these features are not very well supported by the optimization tools, so the utilization of this library is quite difficult. Moreover, some restriction on the model structure are imposed in the optimization tools, for examples the exclusion of the hybrid constructs (conditional expressions or conditional equations to describe discontinuous and conditional models), since the right-hand side of the dynamics is assumed to be twice continuously differentiable. Indeed this limitation excludes optimization of many realistic models, but on the other hand, the reformulation of the discontinuities in smooth approximations may be possible in order to facilitate the optimization.

Starting from the CCPP model, it has been developed another Modelica model that fulfills the restrictions imposed by the optimization tools. The first step in the model realization was to make a compatibility analysis of the CCPP model with the optimization tools requirements, and the following main sources of incompatibility (syntax reduced, discontinuous models, conditional models, etc.), were found:

- Piecewise affine approximation of nonlinear functions;
- Parameterization for the generality of components;
- Absolute value;

- Behavior around zero/division by zero;
- Reversible flow;
- Change of the laws with respect to threshold;
- Switch control variable;
- Steam/water tables.

The second step was to modify all elements of CCPP model which belong to the ThermoPower library, so that each component has to respect the syntax requirements, to be smooth and with a limited use of the inheritance mechanism.

The challenge was to simplify the model elements as much as possible while keeping a good precision of the model. The main features of the Modelica smooth model are:

- Unlike the elements from ThermoPower library, level of detail of the Modelica smooth model is not flexible and the flow reversal is not supported.
- In the thermal power plants there are mainly two types of fluid (water/steam and ideal gas mixture), for these two fluids specific models are defined. This approach is applied to all model elements, to eliminate the conditional equation for parameterization for the generality of components, so the „general" form of the models is reduced to a „particular" form. As an example for the model that describes the flow of the fluid in a tube there is no modeling option to specify the friction coefficient, the dynamic momentum term or the hydraulic capacitance.
- For syntax limitation of type absolute value (*abs(x)*, expanded into "*if x >= 0 then x else –x*") that will cause events to be triggered at points where the function is discontinuous, the initial form is replaced with the square root of the square value, e.g. *abs(x) = sqrt(x*x)*.
- To eliminate the constructs for expressing hybrid models (conditional expressions, conditional equations), the continuous representations are used [19]. The construction of this type of representations is based on using the continuous approximations of the Heaviside function.

$$\forall x \in R, \quad H(x) = \begin{cases} 0, x < 0 \\ 1, x \geq 0 \end{cases} \tag{1}$$

The Heaviside function approximation (smooth approximation) used to define the continuous representation is:

$$\forall x \in R, \quad H_k(x) = \frac{1}{1 + e^{-k * x}} \tag{2}$$

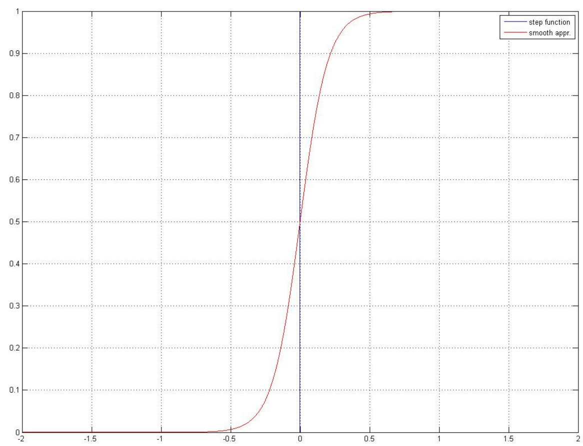


Figure 8: H_k representation for k=10

The most difficult part in the Modelica smooth model realization was to approximate fluid property calculation (steam/water tables). Medium models for water, steam and ideal gas mixtures are included in Modelica Standard Library [17]. A medium model defines algebraic equations for the thermodynamic variables used in the mass and energy balance of component models.

The model for the fluid properties is according to the IAPWS/IF97 standard [16] and is relied on a set of equations for different regions which cover the following range of validity:

$$273.15\,[K] \le T \le 1073.15\,[K] \qquad p \le 1000\,[bar]$$
$$1073.15\,[K] < T \le 2273.15\,[K] \qquad p \le 100\,[bar]$$

The entire range of validity of IAPWS/IF97 is divided in five regions (Figure 9):

- region 1 for the liquid state from low to high pressures;
- region 2 for the vapor and ideal gas state;
- region 3 for the thermodynamic state around the critical point;
- region 4 for the saturation curve (vapor-liquid equilibrium);
- region 5 for high temperatures above 1073.15 [K] (800 [°C]) and pressures up to 100 [bar].

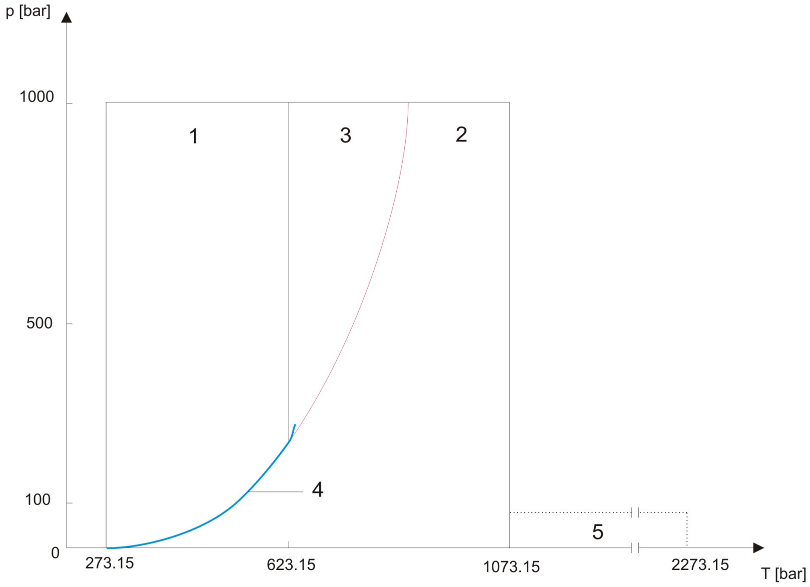


Figure 9: Regions of IAPWS/IF97

Also from Figure 9 it can be seen that for the variation domain of CCPP (p∈ [1-130 bar], T∈ [290–865 K]) only three regions are used (1, 2, 4).

Due to the general design of the Modelica medium models, in the library there are many types of functions used to compute the substance properties. These models have been simplified, keeping only the functions that are used in the CCPP model, and each function has been approximated.

In order to approximate the fluid property functions the following method is used:

1. the value of function in N[2] points from the variation interval is calculated;
2. the Matlab Curve Fitting Toolbox [14] and the Polyfitn tool [15] are used, to find a mathematical model that fits with these data.

Some property functions can't be approximated directly with this method, for example the function that calculates the temperature as function of pressure and specific enthalpy (*T=f(p,h)*), Figure 10. To approximate these types of functions, a region partition is realized (Figure 11), and for each region a mathematical approximation is found, using the method described above.

[2] N =100 points

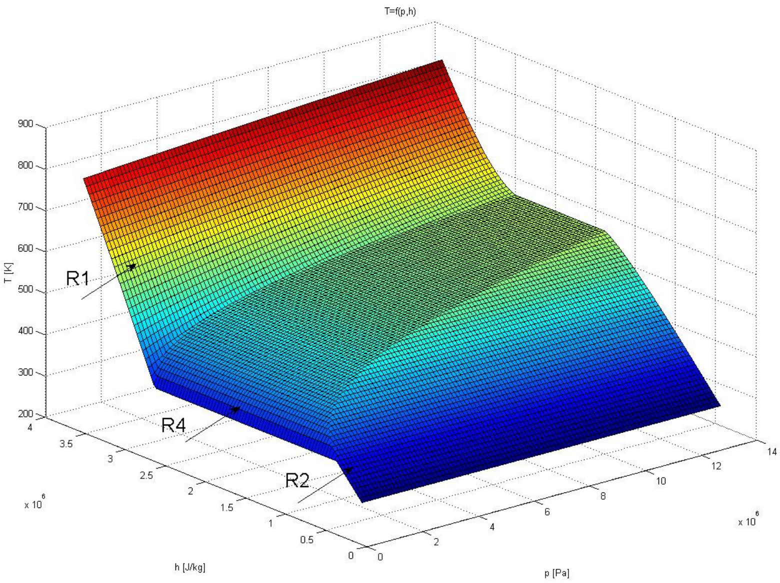


Figure 10: The temperature as function of pressure and specific enthalpy (*T=f(p,h)*)

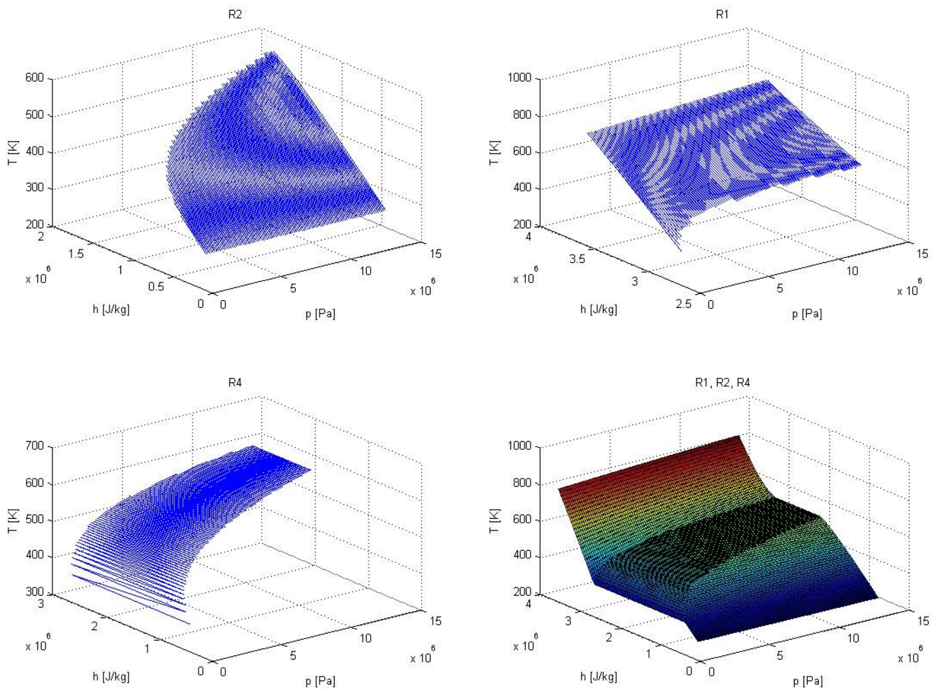


Figure 11: Cutting by regions

Using the fitting tools a mathematical model (polynomial function), for each region: f_{R1}, f_{R2}, f_{R4}, with a high goodness of fit (R-square ≈ 1, RMSE close to 0), is obtained.

To realize a continuous representation of the function, the principle based on the Heaviside function approximation described above is modified, by considering the boundary functions among regions, so that the new smooth approximation used to define the continuous representation is:

$$H_{k_1}(x) = \frac{1}{1+e^{-k_1*(x-b14)}} \quad (5)$$

$$H_{k_2}(x) = \frac{1}{1+e^{-k_2*(x-b24)}} \quad (6)$$

where *b14* is the boundary function between the region 1 and the region 4 and *b24* is the boundary function between the region 2 and the region 4 (Figure 12).

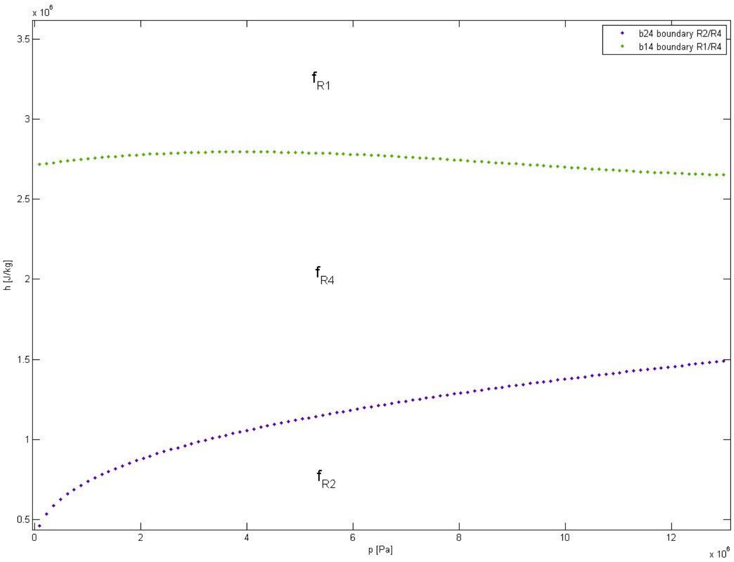


Figure 12: Boundary functions representation

Finally, the continuous approximation of the function will be a smoothed version of the membership condition.
For example, for a function defined on 2 regions:

$$f = w * f_1 + (1 - w) * f_2 \quad (7)$$

where f_1, f_2 are the functions for each region, and w is a binary variable related to these regions, $w = 1$ if the thermodynamic variable belongs to region 1, and $w = 0$ if the thermodynamic variable belongs to region 2. Accordingly, the smooth approximation of the temperature function (Figure 13) is of the form:

$$f_T = (1 - H_{k_1}) * f_{R1} + H_{k_2} * f_{R2} + H_{k_1} * (1 - H_{k_2}) * f_{R4} \quad (8)$$

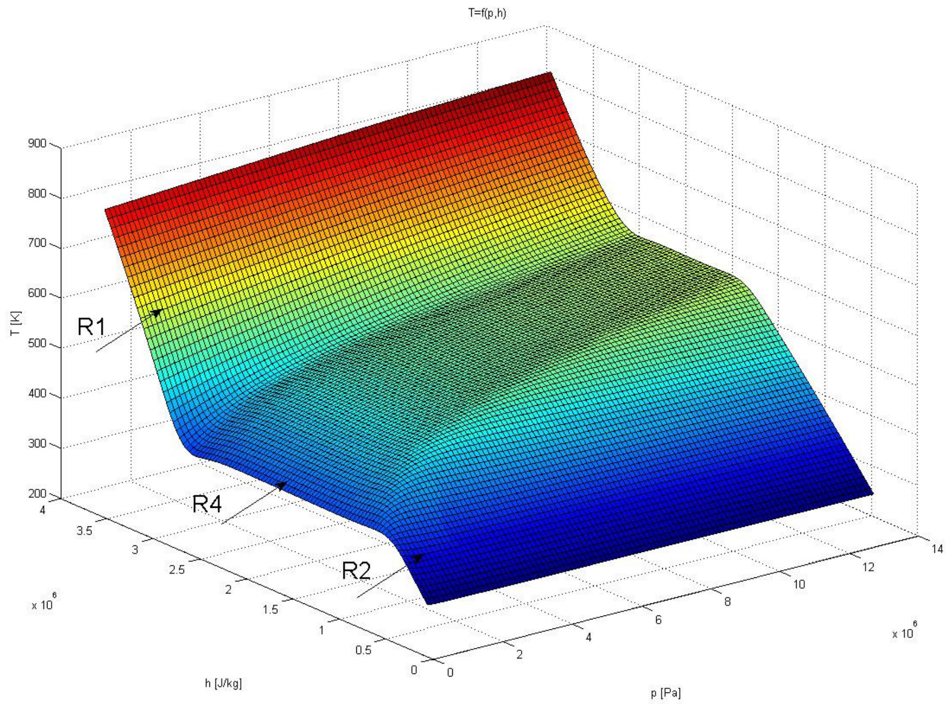


Figure 13: The temperature as function of pressure and specific enthalpy using smooth approximation

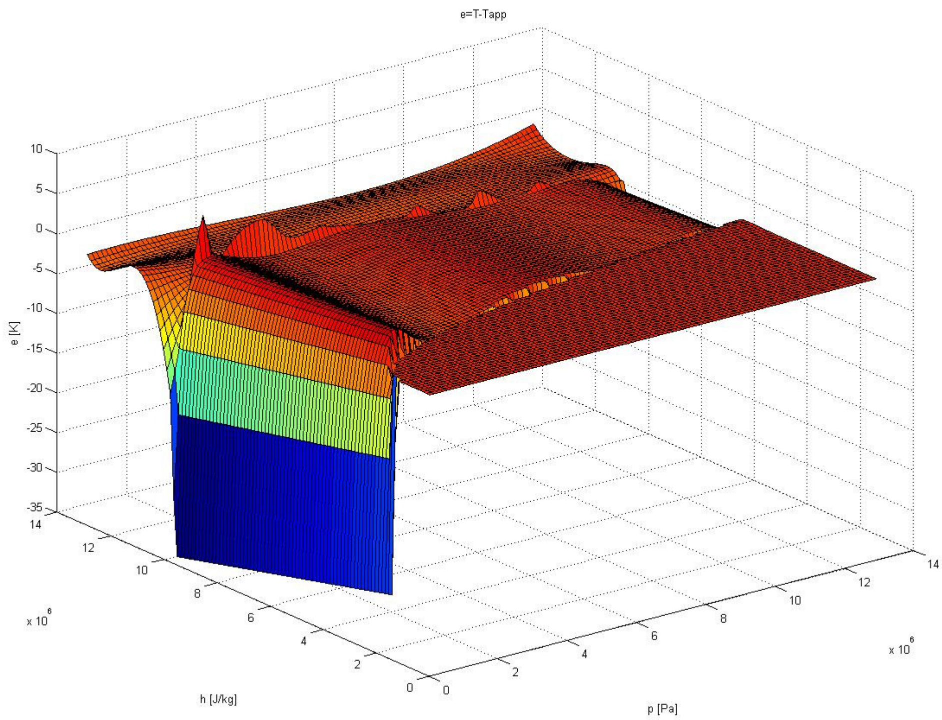


Figure 14: Error representation (*e=T-Tapp*)

As shown in the Figure 14, the smooth approximation is quite good, with small errors, except for the first part of the variation interval (0-5 [bar]), where the errors are higher, around 35 [K]. These errors derive from the approximation of the function for the region 4, f_{R4}. A refining of this function will reduce the size of errors, but it is not necessary since the variation domain of the model considered (with only HP circuit), for a hot start-up is in general greater than 5 [bar].

For the models that use piecewise affine approximations of nonlinear functions i.e. GT model, where the gas temperature and gas flow rate are prescribed as a piecewise linear functions, the same method as above is applied, e.g. for the GT model these functions have been approximated by polynomial functions.

The Modelica smooth model (Figure 15) will be used to test the compatibility with the optimization tools, and to optimize the first stage of the start-up sequence. As can be seen in Figure 15 the model doesn't integrate the Steam Line and Steam Turbine models, it is made of the GT, the HRSG, the valve/bypass circuit and the condenser. Indeed for the present, the goal is to use this model to optimize the first stage of the start-up procedure, and in this stage the ST is stopped, so the modeling of this unit is not required. The ST model is replaced with a valve circuit (admission valve and pressure sink), for the model coherency and also it will be used in the initialization phase of the model (shutdown sequence, see appendix A). Concerning the SL, at the start-up its main objective is to avoid condensation and to get steam quality, necessary for the ST operation. For the considered start-up conditions, the level of condensation is quite low (according to simulation results on the initial model), and practically the SL is only a negligible transport delay between HRSG and the ST, therefore this component is neglected.

The smooth model has 5 input signals (GT_Load, Feed_Drum, Feed_DSH, Bypass_ST, Valve_ST), 6 output signals (GT_Power, GT_Fuel, Drum_Level, T_SH, T_SL, Steam_Press) and.the complexity is the following:

- The DAE has 1541 scalar unknowns and 1541 scalar equations;
- Number of components: 143;
- Variables: 1693 of which:
    - Constants: 136 (290 scalars);
    - Parameters: 529 (594 scalars);
    - Unknowns: 1028 (1541 scalars);
- Continuous time states: 28 scalars.

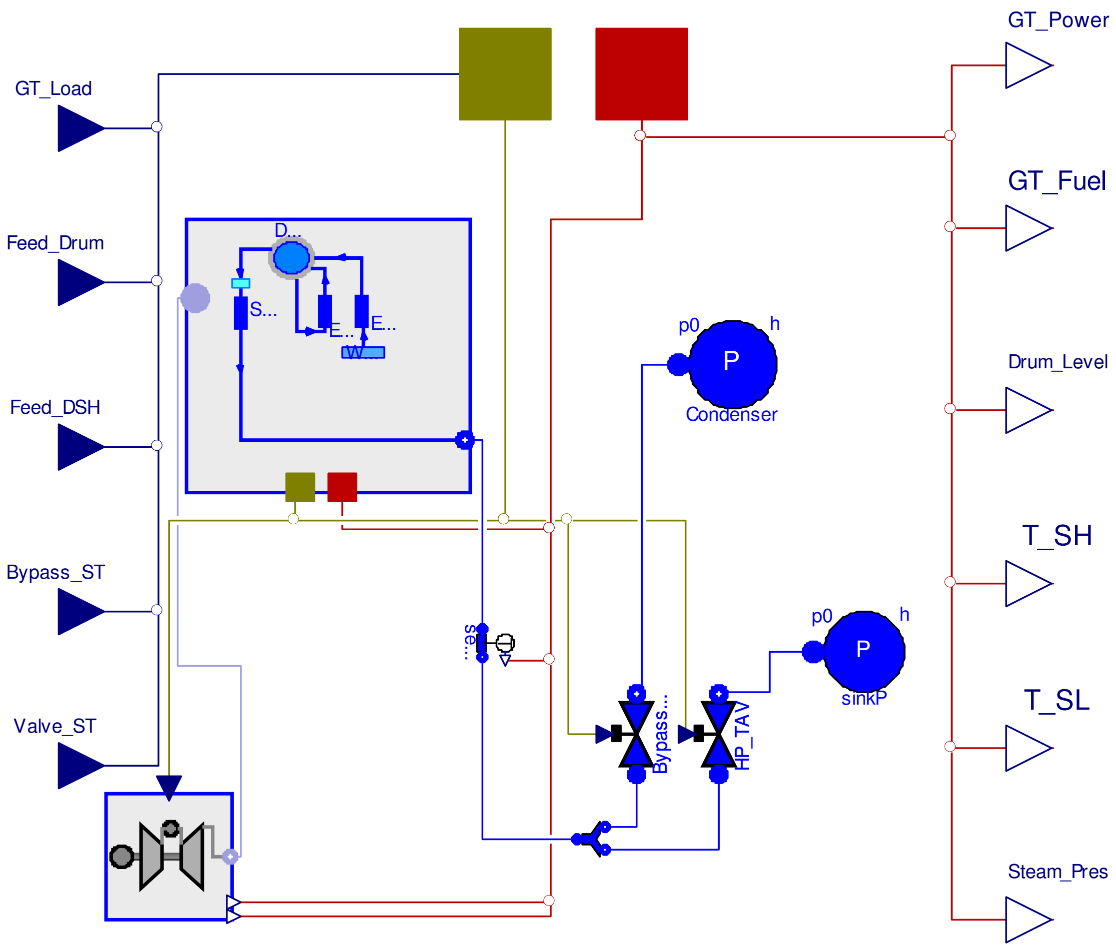


Figure 15: Modelica smooth model

3.1.2 Validation

The Modelica smooth model is compared with the CCPP model responses. The model is initialized in the hot stat-up state and the first three scenarios presented in §2.3 are simulated. In general the parameters that are investigated are the steam temperature and the steam pressure. The evolution of these parameters by comparison with the CCPP model is presented below.

Scenario 1

The gas temperature (T_Gas), the steam temperature in the superheater (T_SH) and the steam pressure (Steam_Pres) of each model are presented in Figure 16.

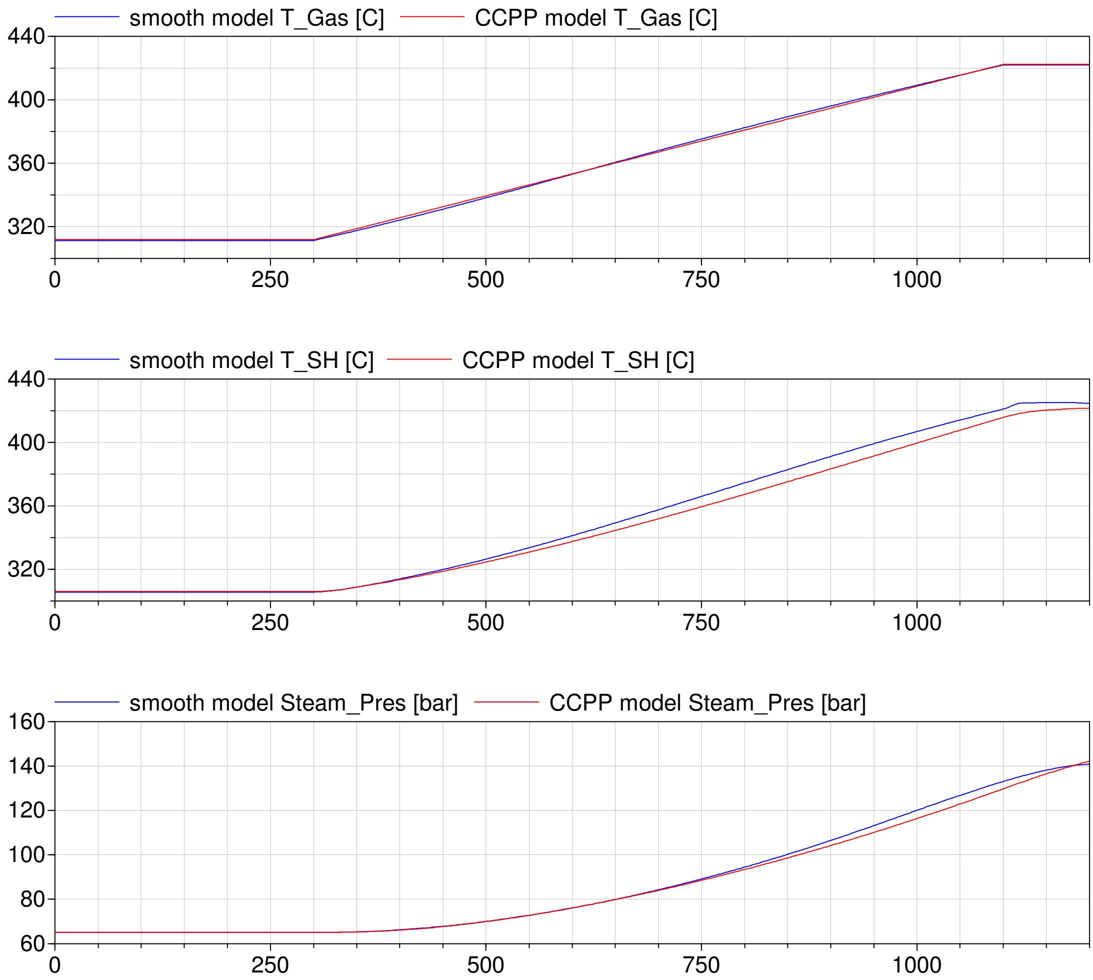
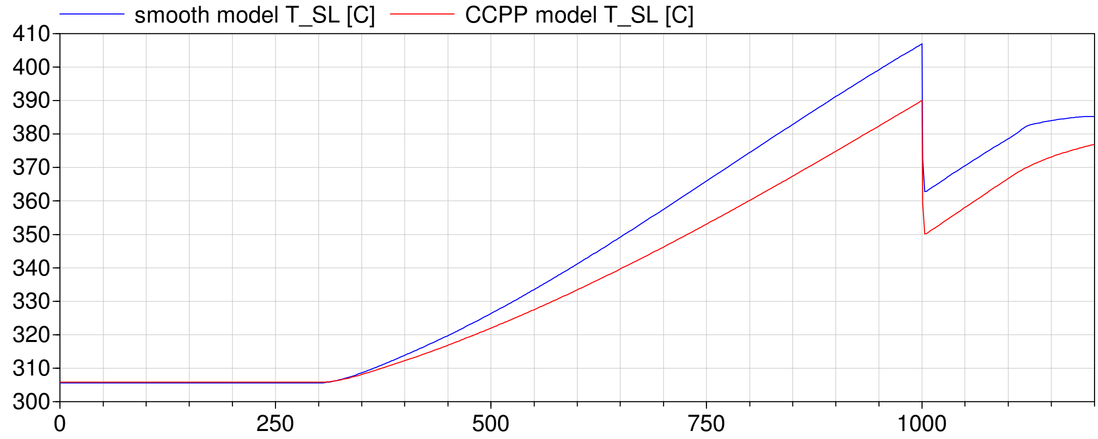


Figure 16: Comparison between the models parameters behavior for the first scenario

As shown in Figure 16, the gas temperature of the smooth model is very close to the gas temperature of the CCPP model, this means that the approach used for the GT model is quite good. Also the quality of the smooth model is shown by comparing the steam temperatures in the superheater and the steam pressures respectively.

Scenario 2

The steam temperature after the desuperheater action (T_SL) and the steam pressure (Steam_Pres) of the models are shown in Figure 17.



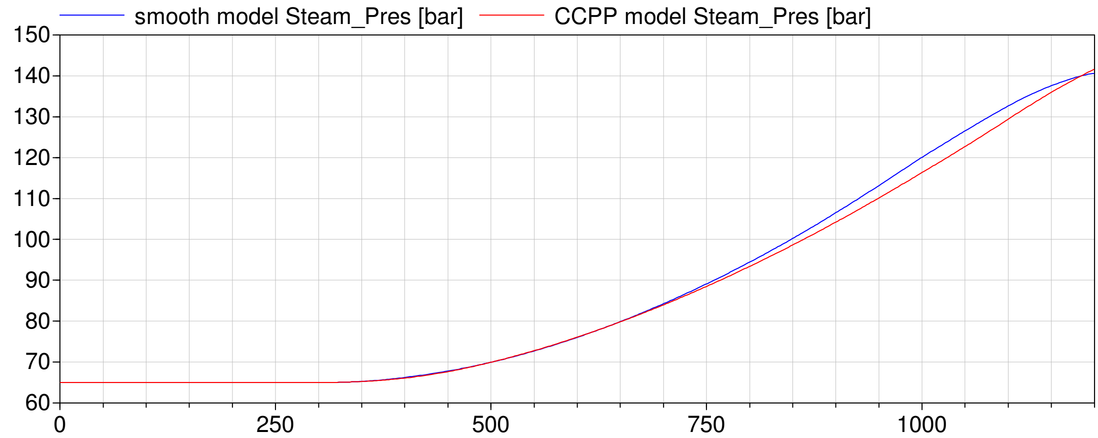


Figure 17: Comparison between the models parameters behavior for the second scenario

It can be remarked from the Figure 17 that the steam pressures are quite close and related to the steam temperatures, there is a more significant difference than in the previous scenario, generated especially by the precision of the approximated functions and the SL unit neglecting.

Scenario 3

The steam temperature in the superheater (T_SH) and the steam pressure (Steam_Pres) of each model are depicted in Figure 18.

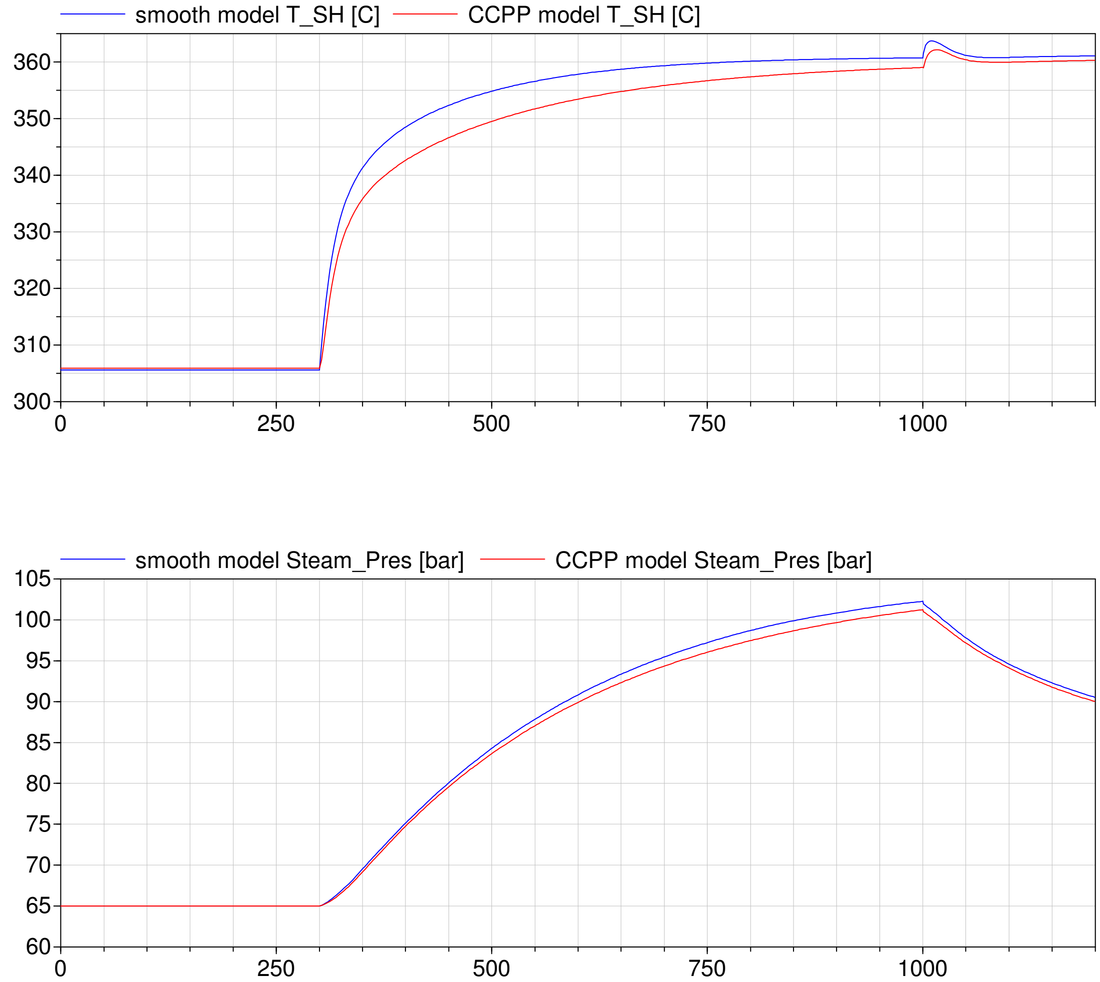


Figure 18: Comparison between the models parameters behavior for the third scenario

For this scenario, as shown in Figure 18, it can be observed a slight difference between the values of the steam temperature and steam pressure of the models.

3.1.3 Conclusion

The components of the ThermoPower library contain a lot of discontinuities incompatible with the gradient based optimization software envisaged to use for control. A smooth model has then been developed and compared with the original one.
Generally, the dynamic behavior of the model is good and the results of the smooth model are close to the CCPP model results (Figure 16, Figure 17 and Figure 18). There are some differences in the parameter evolution mainly due to the precision of the approximated functions and some circuits simplification. These errors could be reduced by improving the precision of the approximation.

3.2 Simulink plant model

The models developed in Modelica, are difficult to use for control purposes, so another model derived from the CCPP model has been developed in Matlab-Simulink. The model represents the main dynamics and is obtained by an identification and interpolation procedure.

3.2.1 Identification and interpolation procedure

<u>Identification</u>

The CCPP model presented above, has been integrated in Matlab (using Dymola-Simulink interface), and the transients have been generated to identify models for different operating points. The identification of each transient of the simulations has been made using the Matlab System Identification Toolbox. The version of the model used for the simulation includes a level controller, and only three inputs of the initial model are considered (GT_Load, Valve_ST, Feed_DSH); the other inputs (BreakerClosed, Feed_Drum and Bypass_ST) are considered constant.

Simulations

Different simulations have been made to generate appropriate identification data. According to the normal functioning of this type of plant, six initial operating points of the gas turbine load have been selected:

- 100% of GT_Load;
- 75% of GT_Load;
- 60% of GT_Load;
- 50% of GT_Load;
- 40% of GT_Load;
- 25% of GT_Load.

For each operating point one simulation is made (over 160 000 seconds) for successive square excitation applied on each input as shown in Figure 19, Figure 20 and Figure 21.

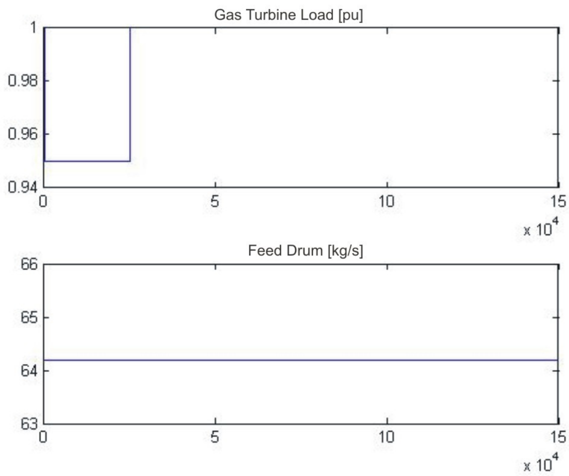


Figure 19: Input example

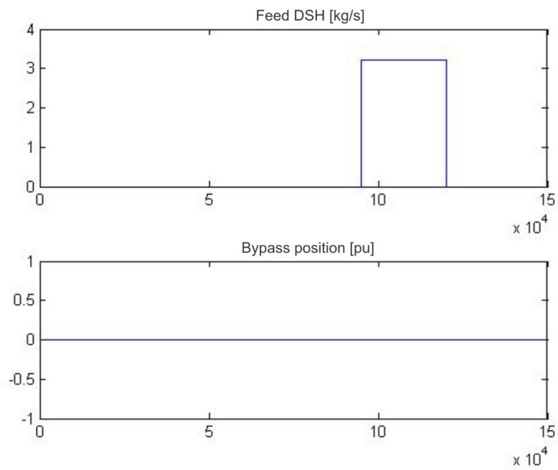


Figure 20: Input example

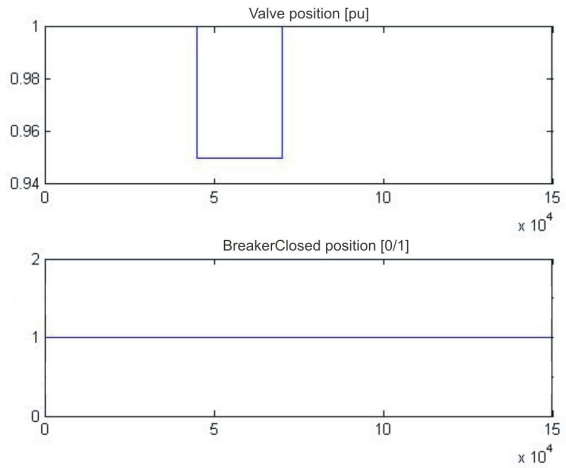


Figure 21: Input example

Linear models are identified with an accuracy of over 90% for each operating point and the different models are interpolated with the method described in the next section.

The first six operating points are not enough to obtain a good behavior of the interpolated model in comparison with the CCPP simulations. The critical point is near 60% load where the sign of the flue gas temperature derivative changes.
To improve the model precision new points have been introduced:

- 65% of GT_Load;
- 63% of GT_Load;
- 59% of GT_Load;
- 57% of GT_Load;
- 25% of GT_Load;

Interpolation

The idea for the interpolation is to connect the different linear models obtained in the previous section at different operating points [16]. To interpolate them, a membership function approach is used.

In Figure 22, the model for the generic output *i* is shown. The inputs (μ_1, μ_2, μ_3) which enter in the main MISO transfer function *Γ*, composed of the identified SISO transfer functions. Offset values (corresponding to equilibrium point) are withdrawn at the inputs and added at the output.

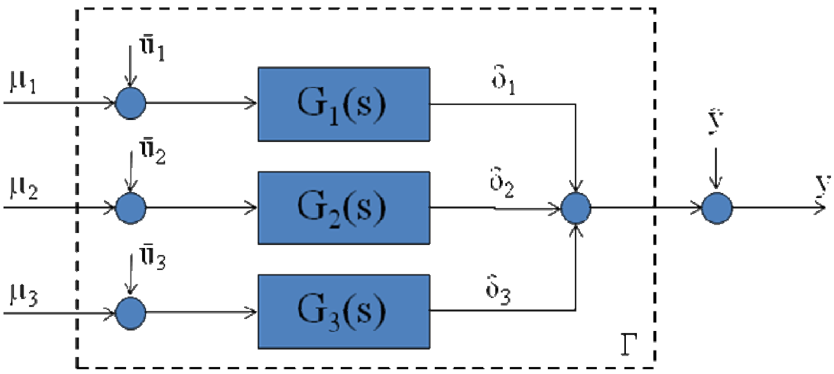


Figure 22: Local Generic MISO Model

In this way it is possible, with three inputs, to obtain the modeling of the transient after a local variation.

The problem is to represent the system between two operating points, for example when a ramp is given on the inputs. Membership functions approach achieves that interpolation, weighting on the nearest model to have a bigger contribute than the others. Because the operating points are defined by the GT load μ_1, the membership functions are using this input, as shown in Figure 23, where Γ_i represent the different operating points.

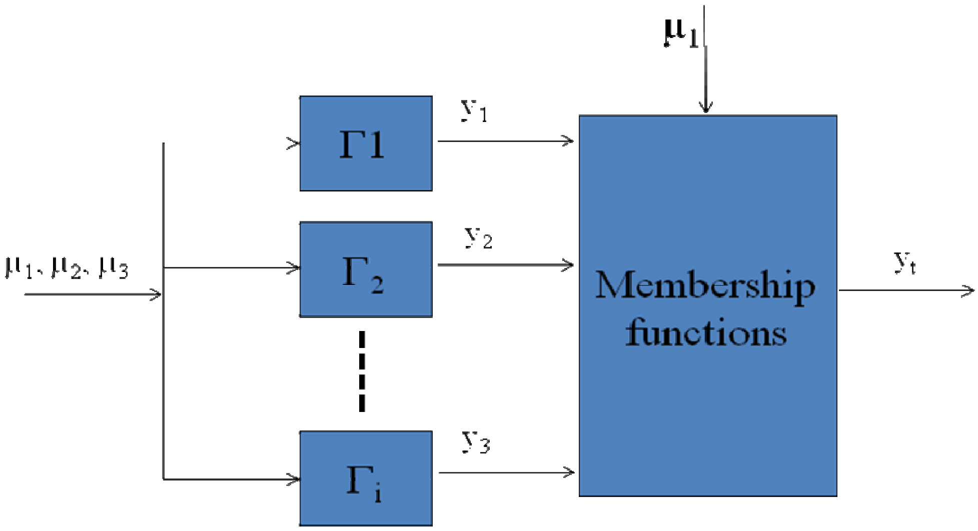


Figure 23: Global interpolated MISO model with membership application

The used membership functions are shown In Figure 24. It is very important to note that in every point the sum of two adjacent membership functions is one. Then, as in the figure, the absolute value of the slope of two adjacent functions must be the equal to guaranty this property.

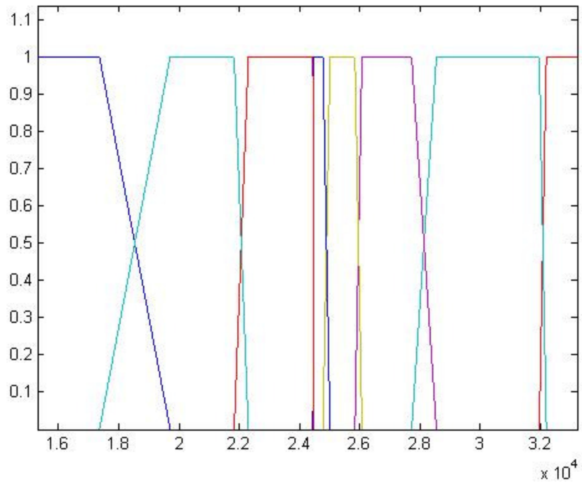


Figure 24: Example of membership function

3.2.2 Results

To assess the quality of the Simulink model over the whole range, the results obtained have been compared to the Modelica/Dymola model on a GT load ramp transient. For example, temperature of the steam in superheater, Simulink curve (green) is close to the Dymola curve (blue) (Figure 25). Another example that shows the quality of this approach is given by the steam pressure evolution (Figure 26).

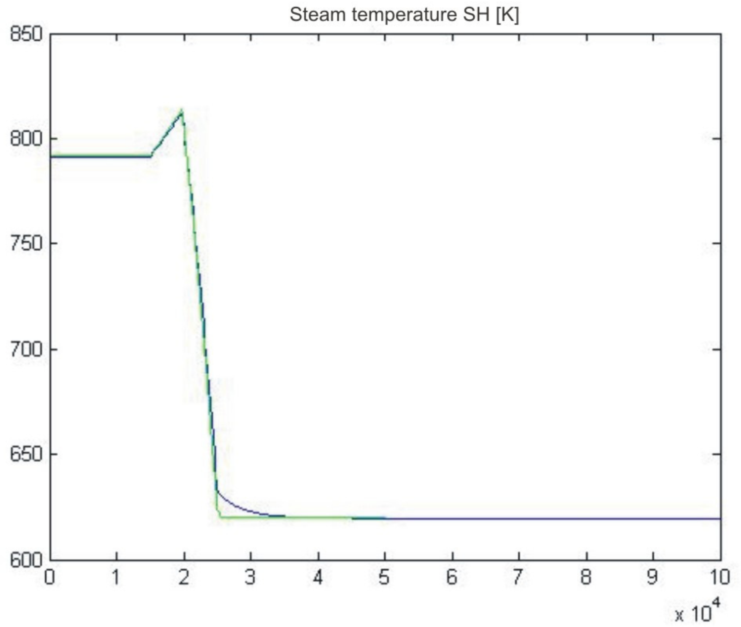


Figure 25: Comparison between the steam temperatures

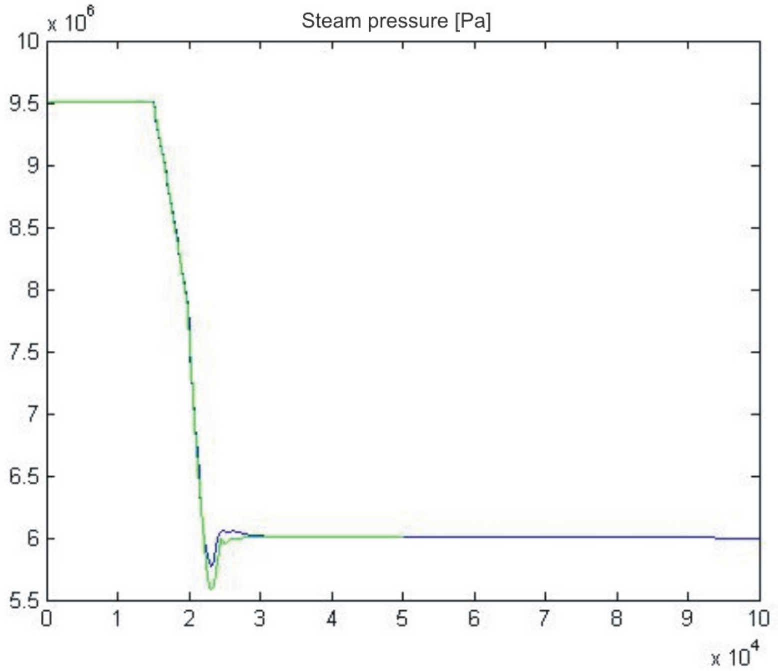


Figure 26: Comparison between the steam pressures

To obtain a model valid for every output variable, it is important to tune the membership functions and the offset values of each output. With this approach, it is also possible to control the precision not only for large disturbance, but also for local variation. It is important to note that the linear identified models must be good to obtain a precise representation of the Dymola model.

4 General conclusions

In this report, three types of combined cycle power plant models are presented: a complex model developed in Modelica/Dymola, and two control models, a Modelica smooth model and a Simulink model.

The Modelica CCPP model is designed with components from the ThermoPower library and parameterized with data from a typical unit. Because of model consistency, the initial conditions specified by the model correspond to the full-load steady state of the plant. The model initialization in the state corresponding to the hot start-up is achieved by loading a dedicated initial state file obtained by a shutdown transient. As the complexity of the Modelica CCPP model is quite high, it is used as a reference for the development of more simplified models for control purposes. Also the Modelica model will be used for validation of control solutions and to carry out the performance analysis of the control solutions.

For control purposes two models have been built: a Simulink model obtained by an identification and interpolation procedure and a Modelica smooth model, both based on the CCPP model. Relating to the Modelica models, it must be emphasized that the use of existing optimization package for control purposes implies some restrictions (for instance switching conditions are not accepted). A Modelica smooth model has been elaborated respecting these restrictions. The control models (Modelica smooth and Simulink) represent the evolution of the main variables of the plant and have been validated against the initial CCPP model.

The next step for the combined cycle plant application will be to use the Simulink and Modelica smooth model in a HD-MPC control design. Concerning the Modelica model, a HD-MPC controller will be computed with an optimization tool (DyOS, JModelica) and tested in simulation. After this optimization, a further step would be to develop a more precise Modelica smooth model that includes the steam lines and the steam turbine components; furthermore the extension of the CCPP model with one level of pressure to a model with three levels of pressure is envisaged. A three levels of pressure Simulink model will also be identified when the corresponding Dymola model will be available.

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6 Appendix: One pressure level CCPP model

1. Model package

The CCPP model is developed using the Dymola 7.2 / Modelica (version="2.2.2") environment and based on the ThermoPower library (version "2.0" or "2.1").

To compile and simulate the model, it is necessary to load the ThermoPower library, which can be downloaded from internet (http://sourceforge.net/projects/thermopower/files). ThermoPower is developed by POLIMI and is open Modelica library for the modeling of the thermal power plants, more information about it, can be found on http://home.dei.polimi.it/casella/thermopower/.

The model is delivered in an archive (*.zip*) that contains the following files:

- the Dymola/Modelica model (*.mo*),
- the file with the initial conditions (*hot_start_state.txt*),
- the script (*.mos*),
- the file with the initial value of the input signals (*dsu.txt*)

Because of model consistency, the initial conditions specified by the Modelica model correspond to the full-load steady state of the plant. A specific procedure described below has been used to define the hot start-up initial state that is saved in the file '*hot_start_state.txt',* delivered within the archive. This initial state has to be loaded (using the Import Initial command) after the model translation. A file with a script that realizes these steps is also provided.

Therefore, to initialize the model with the hot start-up state in Dymola, it is necessary to:

1. Open the Dymola/Modelica model,
2. Translate the model,
3. Import the *hot_start_state.txt*

or

1. Run the *script.mos*

After that the model can be simulated.

2. Model specifications

The plant model developed (in accordance with deliverable D7.1.1), is made of one gas turbine (GT), one heat recovery steam generator (HRSG) with a single level of pressure, one steam line (SL), one single stage steam turbine (ST) and one element of type sink, that practically represents the condenser.

The model has 6 input signals, 10 output signals and 53 state variables.

The inputs are:

- GT_Load – the load of the GT [pu],
- Feed_Drum – the feedwater flow rate for the HRSG circuit [kg/s],
- Feed_DSH – the water flow that feeds the desuperheater [kg/s],
- Bypass_ST – the bypass position [pu],
- Valve_ST – the admission valve position of the ST [pu],
- BreakerClosed – the generator grid breaker of the ST [0/1].

The outputs are:

- GT_Power – the GT power [W],
- GT_Fuel – the GT fuel flow [kg/s],
- Drum_Level – the drum level [m],
- T_SH – the steam temperature in the Superheater Header (at the output of the HRSG) [°C],
- Steam_Press – the steam pressure [bar],
- Header_Stress – the Header thermo mechanical stress (ASME standard) [Pa],
- T_SL – the steam temperature in the Steam Line (at the output of the SL) [°C],
- ST_Power – the ST power [W],
- ST_Frequency – the ST frequency [Hz],
- ST_Stress – the ST rotor thermal stress [Pa].

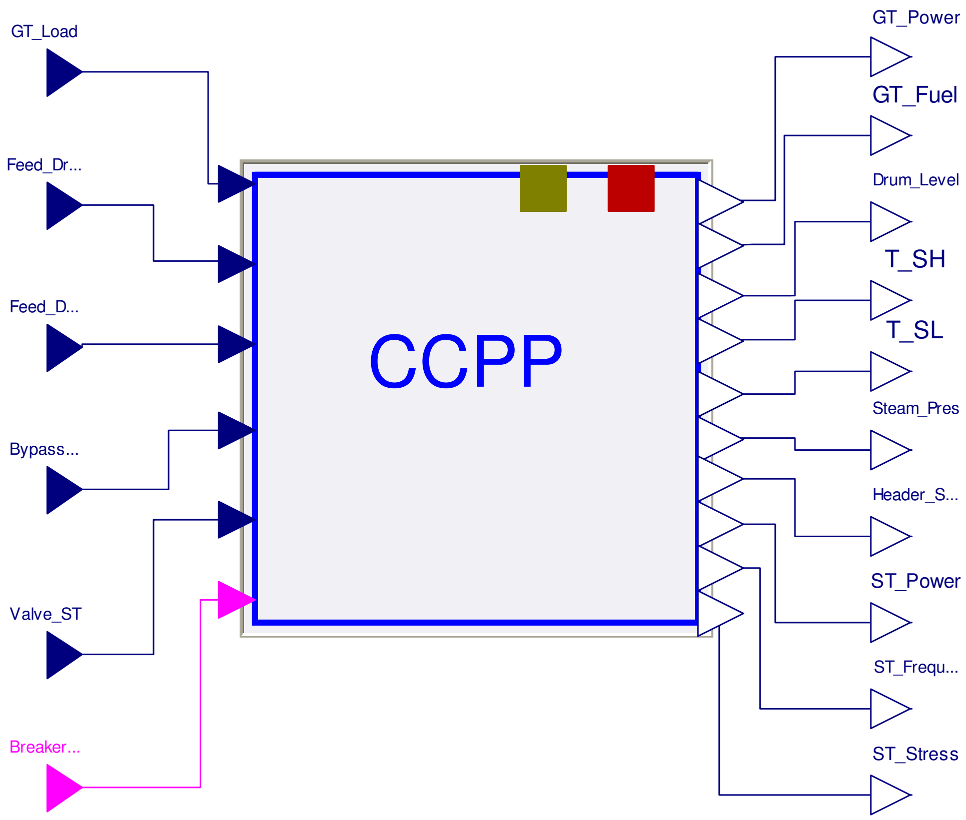

Figure A1: The implemented Dymola/Modelica model

2.1. Model components

The plant model is provided as a Modelica component (Figure A1). It includes five components connected by thermo-fluid connectors (see the ThermoPower library) as shown in Figure A2. The input and output signals are composed in signal buses (green for inputs, red for outputs) in order to make the connections simpler.

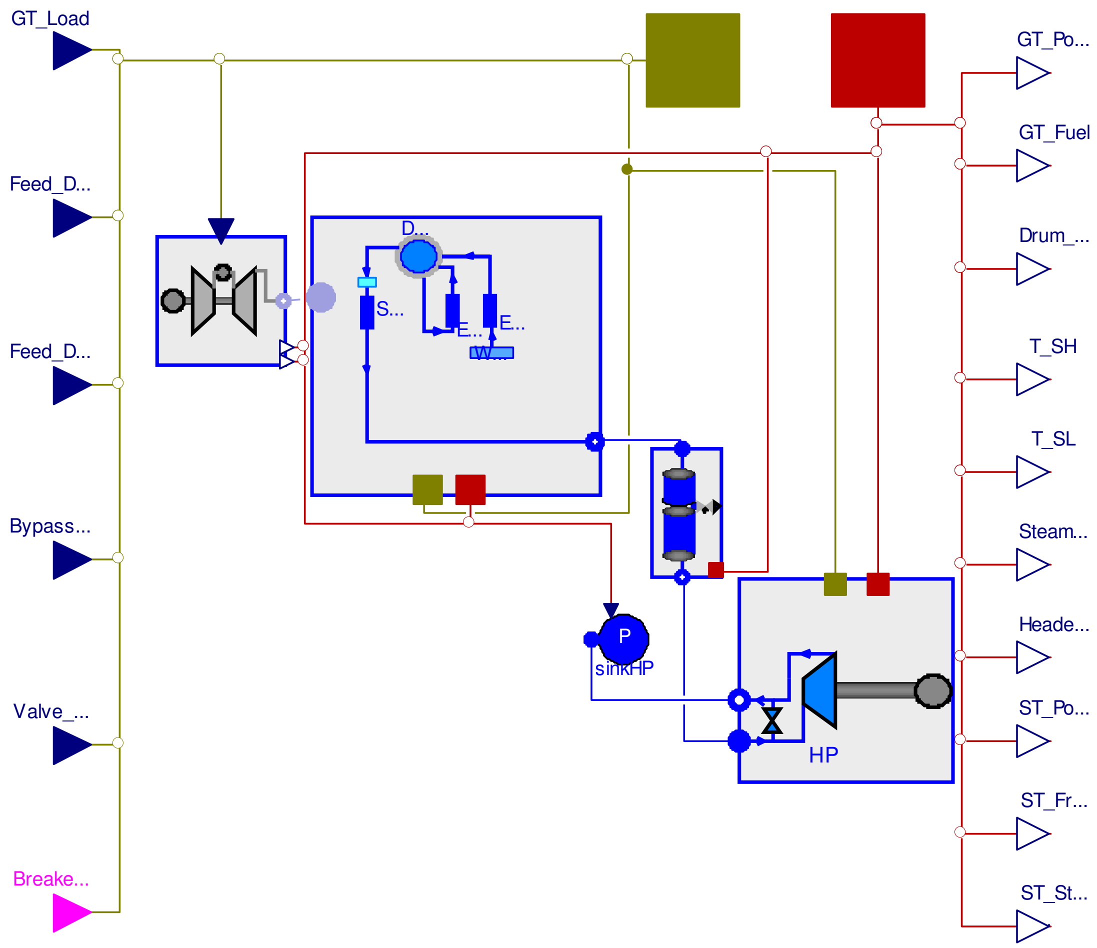

Figure A2: Configuration of the plant model

Gas turbine [ThermoPower Library]

The model of the GT unit used is a component from the ThermoPower library. The GT unit is modeled into a simplified form (as an ideal source of hot gases, whose temperature and flow rate depend on the load level).

Heat Recovery Steam Generator

The HRSG model (Figure A3) is made of components from the ThermoPower library:

- a drum model,
- three heat exchangers along the gas path (one economizer, one evaporator and one superheater),
- a desuperheater (attemperator) composed by a source flow and a mixer,
- a source of water to feed the circuit,
- a circulation pump,
- a steam header,
- three sensors for the steam (temperature, pressure, flow),
- a pressure sink for the gas flow.

Heat Exchanger
The HE model from ThermoPower library includes the fluid flow models, the heat transfer models, and the metal wall model. The fluid flow model on the water/steam side is replaceable, so the HE can be used to describe one-phase HE (economizer ECO_HP, superheater SH_HP) or two-phase HE (evaporator EV_HP).

Drum
The HP drum model is based on mass and energy balances, assuming thermal equilibrium between the two phases.

Steam Header
The steam header is used to calculate the thermal stress.

Desuperheater
It used to reduce the steam temperature. The desuperheater is composed of a flow rate source and a constant volume mixer with metal walls.

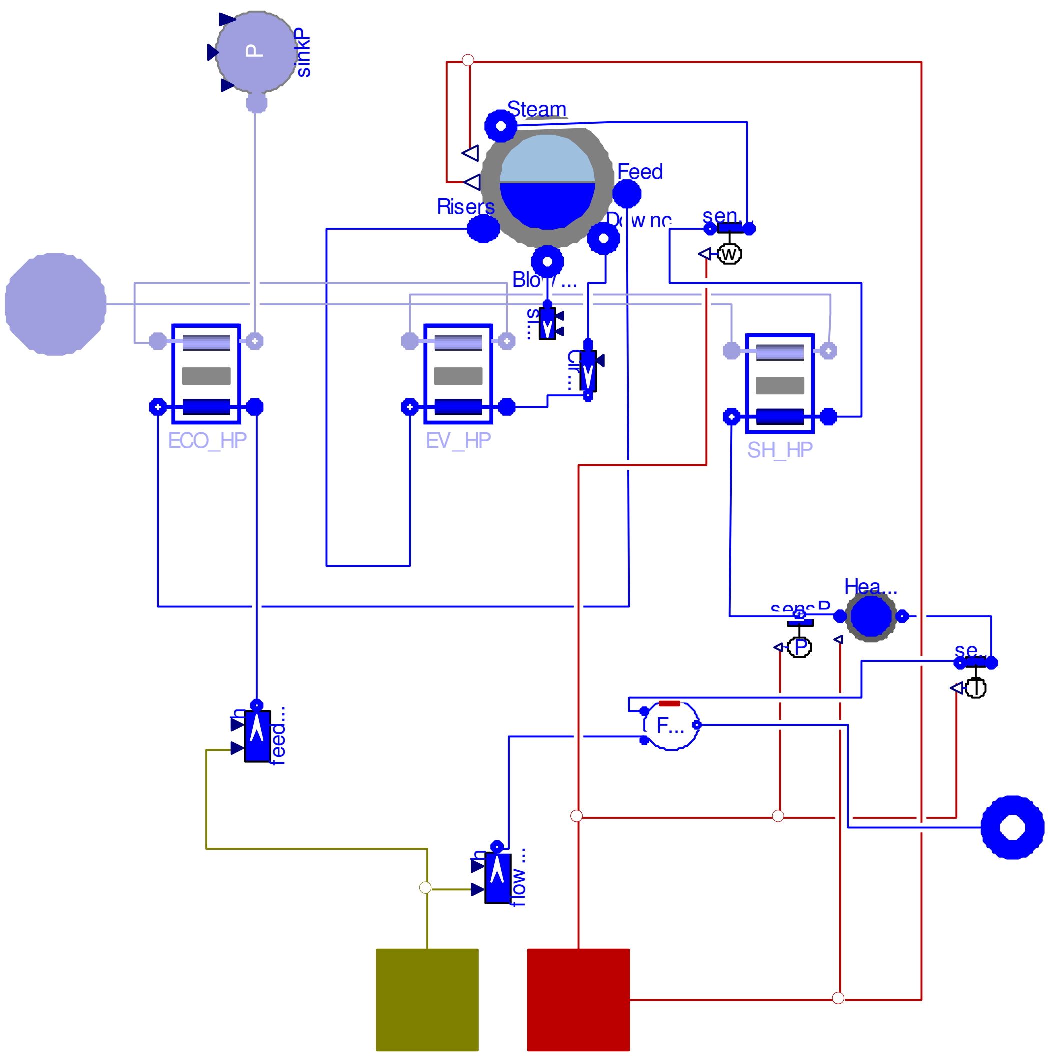

Figure A3: The HRSG model

Steam Line

The Steam line model (Figure A4) is composed of a system of pipes with isolation, a water box model with sink, used to eliminate the condensation and a temperature sensor.

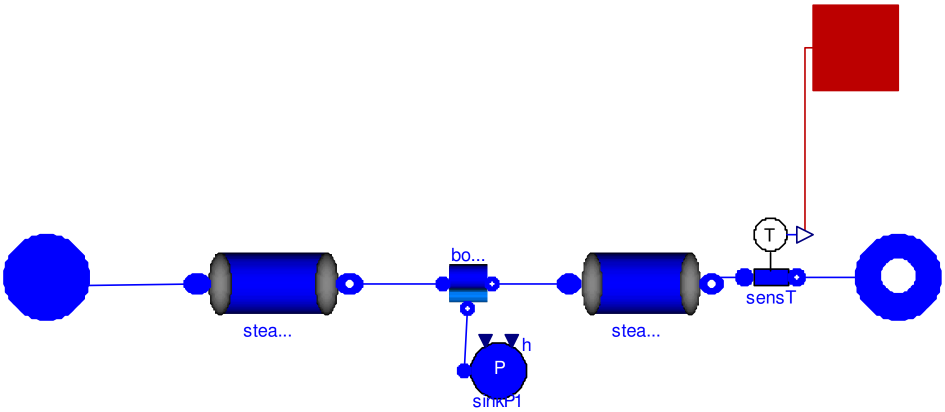

Figure A4: The Steam Line model

Steam turbine [ThermoPower library]

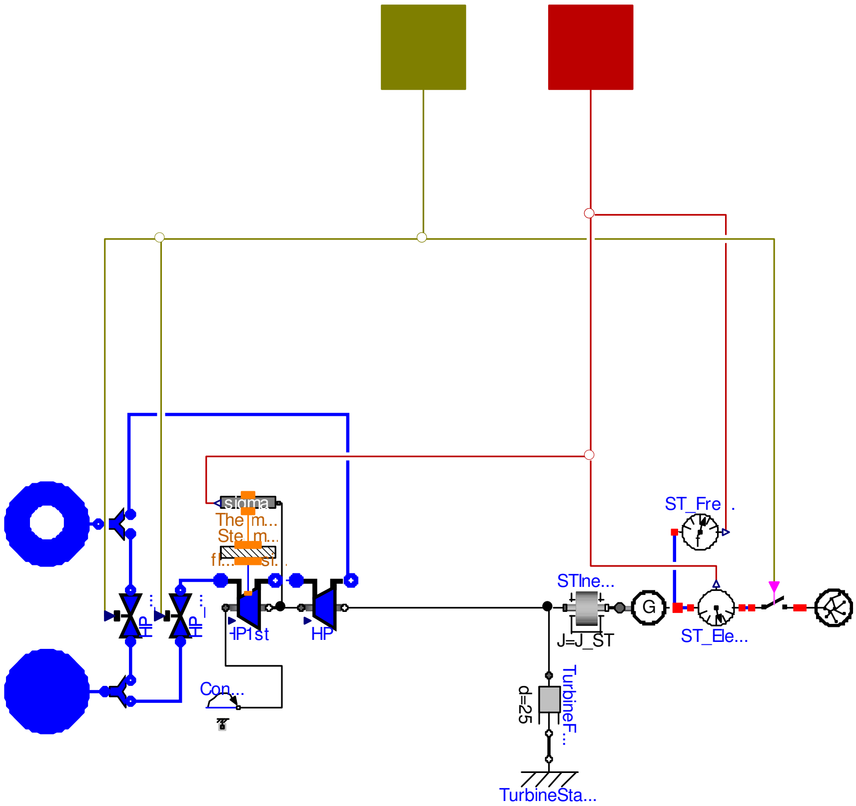

Figure A5: The Steam Turbine model

The ST unit model (Figure A5) includes the high pressure turbine, a stress model and the turbine bypass/valve circuit. The turbine model is completed by the inertia, the electrical generator and the connection to the grid models.

SinkHP

This element is used to collect the HP steam. The sink pressure is prescribed as a function of the steam flow rate.

2.2. Initial state

The initialization of the plant model in the shut-down state is difficult (insufficient knowledge of the initial values, low or zero flow rates) therefore the Modelica model is initialized near the full-load steady state.

The model is brought to a state corresponding to the hot start-up of the plant by a shut-down sequence: the model is initialized nearby the full load (GT=235 MW), after 600 s the bypass valve is closed and the admission valve is opened. At 900 s the steam is fully admitted into ST (the bypass is closed and the admission valve is full-opened). After 1h, the shut-down transient begins (the bypass is opened, the valve is closed, during 400 s and the GT load is gradually decreased until 0.075. The system is kept with GT_load = 0.075, over a few hours (to avoid the singularities in the flue gas side model, a small flow rate has to be held). This state has been saved in the file (*hot_start_state.txt),* and specifies the initial state for the hot start-up.

With respect to the sequence specified in HD-MPC deliverable D7.1.1 (page 18), this state coincides with the middle of the second stage, *HRSG Start-up phase,* when the GT is synchronized and the HRSG is ready (the temperature condition is accomplished, that means the Superheater metal temperature is greater than steam temperature). The first stage, *Preparation phase* (GT start, purge) and also the first part of the second stage, *HRSG Start-up phase* (GT acceleration, HRSG warming), are not considered here because the model of the gas turbine is very simplified.

The state corresponding to the hot start-up of the plant is then:

- ST with no steam flow, stopped (“almost “):
  - Temperature distribution of the turbine shaft around 420 [°C];
  - Bypass opening around 0.16;
  - Admission valve completely closed 0;
- - Generator grid breaker 0 (open);Steam Line:
  - Metal wall temperature around 306 [°C];
- HRSG:
  - Steam pressure 65 [bar] in the HP circuit;
  - Steam temperature around 305 [°C] in the HP circuit;
  - Water flow rate around 8.9 [kg/s];
  - Water flow rate of the desuperheater 0 [kg/s];
  - Drum level around 0 [m] (the drum is measured with respect to the middle of the drum);
  - *Economizer*
    - Metal wall temperature around 281 [°C];
  - *Evaporator*
    - Metal wall temperature around 282 [°C];
  - *Superheater*
    - Metal wall temperature gas side around 307 [°C];
- GT:
  - GT Power around 17.6 [MW];
  - Gas flow rate 454 [kg/s];
  - Gas temperature around 312 [°C];

2.3. Input signals range

2.3.1. Gas Turbine

- 0.075 ≤ GT_Load ≤ 1 (that corresponds to the minimum load (17.625 [MW]) and maximum load (235 [MW]), respectively)*

2.3.2. HRSG

- 3.25 ≤ Feed_Drum ([kg/s])[1a]
- 0 ≤ Feed_DSH ([kg/s])

2.3.3. Steam Turbine

- 0 ≤ Bypass_ST ≤ 1 (close/open)*
- 0 ≤ Valve_ST ≤ 1 (close/open)*
- BreakerClosed 0/1 (1, when the ST is connected to the grid, otherwise 0)

3. Control specification

3.1. Objectives

Four objectives are defined for the control problem at hand, they are:

[1a] Constraint imposed by the Modelica model

* Represent the hard constraints imposed to the input signals

- The first and the main objective of the CCPP start-up, is to optimize the time:
  - minimize the start-up time,
  - “just in time” optimization. The goal is to reach the production point at the specified time.

- The second control goal is to obtain a stable production point at the end of the start-up sequence, which means the power plant works at full load, with practically no oscillations.

- The third goal is to optimize the ratio production/consumption:
  - minimize the fuel consumption of the GT,
  - maximize the GT load. The start-up has to be made with the maximum load ramp possible of the GT.

- The fourth goal is to minimize the material stress.

3.2. Constraints

According to deliverable D7.1.1, the main constraints are related to the stress of some components (especially ST, Header HP, and Steam Line).

3.2.1. HRSG

- Header HP:
  - the acceptable temperature gradient for the steam temperature in the superheater header (T_SH) is 12 °C/min (upper limit);
- Drum:
  - the upper limit of the pressure gradient is 2 bar/min,
  - the level has to be limited between -100 [mm] and 100 [mm], reference point for the level is the centerline of the drum,

The steam temperature should stay under 580 [°C].

3.2.2. Steam Line

The geometry is almost the same as the Header HP (diameter, thickness), and then the maximum temperature gradient is kept at 12 °C/min.

3.2.3. ST

- Valve_ST:
  - it is forbidden to open the valve (Valve_ST) if the steam temperature is not at least 50 °C above the saturation temperature ($T\_SL \geq T\_sat + 50$),
  - the valve opening gradient is limited at 6%/min (this limit takes the different criteria and particularly of the rotor stress into account),
  - when the ST is connected to the grid, the minimum opening of the valve is 10%,
- Speed:
  - the acceptable frequency gradient is 3.6 Hz/min,
- Rotor Stress:
  - the peak stress[2a] accepted is 450 [MPa].

[2a] The stress is calculated by the Modelica model

Glossary

ASME	American Society of Mechanical Engineers
CCPP	Combined Cycle Power Plant
DSH	Desuperheater
ECO_HP	Economizer High Pressure
EV_HP	Evaporator High Pressure
GT	Gas Turbine
HE	Heat Exchanger
HP	High Pressure
HRSG	Heat Recovery Steam Generator
IP	Intermediate Pressure
SL	Steam Line
SH_HP	Superheater High Pressure
ST	Steam Turbine
T_sat	Temperature of the saturation
T_SH	Temperature of the steam in the Supearheater Header
T_SL	Temperature of the steam in the Steam Line