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Executive Summary

The report presents the control specifications for the combined cycle startup. The objectives, the constraints and the robustness requirements are given. This information will be used as input for the HD-MPC design.

1 Introduction

Combined Cycle Power Plants (CCPP) actually represent a very efficient energy conversion technology and a favorite option to satisfy the growing demand of electric all over the world. During the last years CCPP have been continuously installed due to their high efficiency, their low emissions and low investment costs. Nowadays, CCPP maintain higher efficiency levels (up to 60%) than traditional oil or coal fired plants (until 40%) and a reduction of pollutant emissions that have a major importance in view of the constantly increasing restrictions on the concentration of NOx and CO2 by law.

It is important to recall the context in which evolves the current electricity market, to understand the reasons why start-up of combined cycle power plants optimization presents an operational interest. The CCPP have to respond at the daily fluctuations in power demand and as a result of these variations, power plants undergo frequent shutdowns and start-ups. Indeed, many combined-cycle units shutdown nightly and during weekends or more extended periods, thus the power plants are subject to a large number of transients during their operation.

Optimizing start-up can aim at several purposes and should ideally allow the plant operator to:

- reduce the probability of occurrence of missed starts; this is an important point since a missed start corresponds to so much time lost, that the plant generally does not respond to the request from dispatching;
- reduce fuel consumption; significant increase of the gas price obviously makes this criterion more important;
- decrease the startup time is a crucial competitive advantage;
- minimize the environmental impacts during a start-up;
- limit the material wear; this has two effects: it will increase the life cycle of the plant and it will limit the number of maintenance stops.

Several studies have been made to model CCPP in order to simulate and optimize the startup transients. A section on the related work is given at the end of the present report. A stumbling block is the complexity of the process that leads to high order non linear model. Another difficulty is the presence of logical and continuous decision variables that leads to a hybrid optimization problem.

Hierarchical and Distributed Model Predictive control is a promising way to address the startup-optimization problem in its whole. The idea is to split the problem in smaller ones simpler to solve and then to design an upper layer that will send orders to the local optimizations. This decomposition corresponds to the classical hierarchical control with the upper layer implemented in the DCS (Distributed Control System) and the PLC that controls the process locally. With the increasing computational power and communication possibilities of the commercially available DCS advanced optimization solution can be envisaged.

The present report proposes the control specification for the startup of CCPP with HD-MPC. The second section gives a material partition of the plants in subsystems. For each of these subsystems, the existing control and the operational constraints are specified. The objectives functions, the robustness specification and suggestions for the control architecture are given in the sections 3, 4, 5. The section 6 describes the different steps of a start-up sequence. This information will be used in the next steps of the project to build a model of the process and an HD-MPC solution based on a partition to be defined.

2 General description of a CCPP

Combined cycle power plants are power generator units that use two thermodynamic cycles, the Brayton cycle gas turbine and the Rankine cycle steam turbine to generate electricity. The steam turbine is used to recover part of exhaust gas energy and enables higher efficiencies than the gas turbine alone (simple cycle configuration). The two cycles are coupled by means of a heat exchanger from the gas turbine exhaust gas in the Heat Recovery Steam Generator (HRSG) to produce steam. The challenge in these systems is to obtain an integration level that maximizes the efficiency at an economic cost.

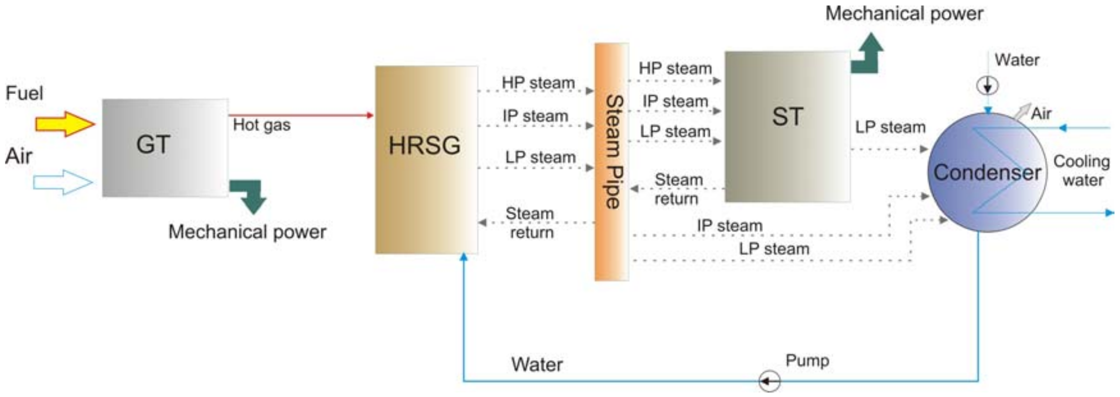

Figure 1: Schematic of a simple CCPP

Figure 1 represents the general configuration of a combined cycle power plant with the main components:

- the gas turbine (GT),
- the heat recovery steam generator (HRSG),
- the steam turbine (ST),
- the condenser,
- the pipes system between HRSG and ST.

There are various configurations of CCPP according to the number of gas turbines, steam turbines or steam generators. In this document a (1-1-1) CCPP with one GT, one ST and one HRSG with three pressure levels will be considered and the normal schematic operation is then the following. Ambient air is compressed, then mixed with fuel and burned in the combustion chamber, where the chemical energy is released to the fluid. The resulting high-temperature, high-pressure gas is expanded in the GT, generating mechanical power. The GT exhaust hot gases are used to produce steam at three different pressures in the HRSG, from the high-pressure (HP), intermediate pressure (IP) and low-pressure (LP) boilers. The steam is expanded in the related (HP, IP and LP) steam turbines to obtain additional power. The steam cycle is completed by feeding the three boilers in the HRSG with the water from the condenser to the LP drum and then from the LP drum to the IP and HP drums.

2.1 Gas Turbine

2.1.1 Description

The Brayton cycle GT is one of the most efficient cycles for the conversion of gas fuels to mechanical power. The GT is the most important equipment of the combined cycle since it provides the main part of the electrical power and supplies the thermal energy needed by the steam cycle. GT is made of a compressor coupled to a turbine and a combustion chamber in between (Figure 2). The compressor compresses the ambient air that is then mixed with fuel and burned under constant pressure conditions in the combustor chamber (C.C.). The resulting hot gas is expanded in the turbine to generate mechanical power.

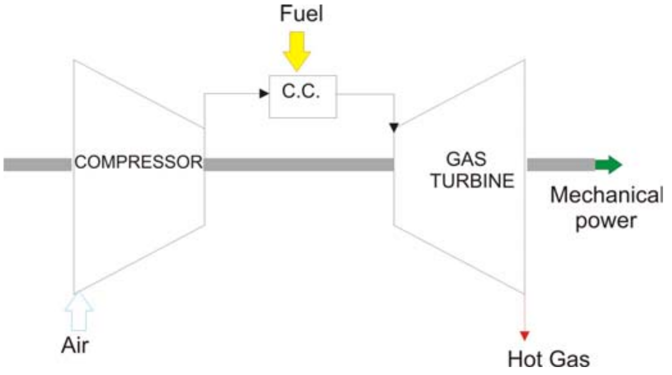

Figure 2: Gas turbine structure

2.1.2 Local control strategy

The functional view of the GT is given in Figure 3. The controlled input variables are the fuel and air flows that are admitted inside the GT. The interaction variables are the hot gas that is exhausted and the generated mechanical power.

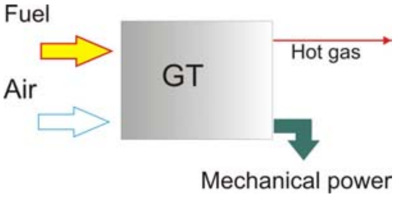

Figure 3: Gas turbine

GT is delivered with its control that manages its start-up. It has three operating modes, each involving a different type of control.

The first mode is the launch mode that is an automatic sequence specified in Figure 4. During the first step “purge”, an auxiliary engine is used to drive the compressor in order to purge the chimney. When this step is completed the GT ignition is switched on (beginning of the step “speed-up”) and the rotational speed is increased to reach a given value (considered here as 75% of its nominal value). At the beginning of the next step (“GT speed”) the auxiliary engine is stopped and the speed is then increased to its nominal value. The associated generator is then synchronized with the electrical network. During these steps the load of the turbine is set at a low value (typically 8%). The transition from the “purge” state to the “speed-up” state may also be constrained by external conditions as it corresponds to the ignition switch-on and the time when the exhaust gas temperature begins to increase.

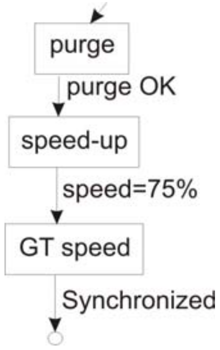

Figure 4: Launch mode of the Gas turbine

The second mode is the temperature matching mode. In this mode, the exhausted gas temperature is controlled according to an input temperature reference signal whereas the load is maintained to a minimal value (typically 8%). This mode will be used to optimize the start-up of the HRSG and of the ST.

The last mode is the taking charge mode. In this mode, the load is controlled according to input reference signals. It is used to lead the GT to its nominal load.

2.1.3 Physical limitations and constraints

The start-up sequence is constrained by many phenomena. The first type of constraints is specified on the gradients of increasing gas temperature and increasing load. The constraint on temperature gradient is mainly considered during the temperature matching mode whereas the one on load gradient is considered during the taking charge mode. The gas turbine output is raised up at a rate of about 2% - 5%/min. This operation can be done either through the DCS or directly by the GT governor HMI.

The system disposes of protection circuits [1], to ensure safety operation and prevent abnormal situations, which could lead to the plant shutdown:

- Overspeed when the speed exceeds the security limit (typically 110%),
- Overtemperature when the average exhaust temperature exceeds the set limit point,

- Overloading when the load of the turbine is too high with respect to its nominal value,
- Loss of flame when fuel/air ratio exceeds the flame extinction limit.

2.2 Heat Recovery Steam Generator

2.2.1 Description

HRSG consists of heat exchangers that use the hot gases from GT to produce steam and to increase the steam temperature beyond the saturation point so that it can be expanded in the ST and can generate additional electrical power.

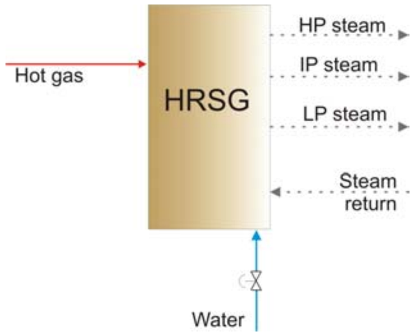

Figure 5: Heat Recovery Steam Generator

There are many different configurations of HRSG units, the one that is considered here is a HRSG with three pressure circuits (Figure 6):

- High Pressure (approx. 100 bar, 80 kg/s, 560°C superheated),
- Intermediate Pressure (approx. 20 bar, 30 kg/s, 550°C superheated),
- Low Pressure (approx. 5 bar, 10 kg/s, 150°C saturated)[1].

A schematic representation of the three circuits is given in Figure 6. Each circuit produces steam at a given pressure from water. The LP section is fed with water from the condenser while the IP, HP sections are fed with water that has been heated by the LP circuit. The IP circuit is also fed with the steam return from the HP steam turbine.

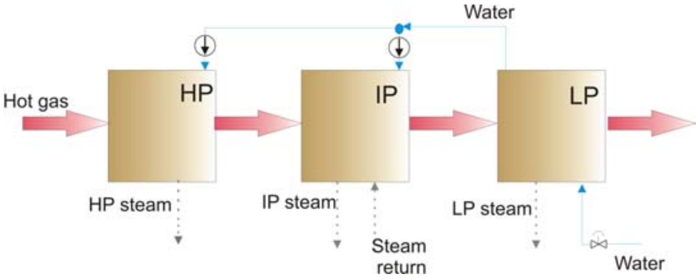

Figure 6: HSRG decomposition

Each HRSG circuit (for example the HP circuit in Figure 8) is made of the following components:

1. Economizer (ECO). The economizer is used to preheat the feed water introduced in the steam drum in order to replace the steam produced and delivered. It is normally located in the colder gas, downstream the evaporator (see Figure 7).
2. Steam drum. A steam drum connects the economizer, evaporator and the superheater. The cross section of the drum is circular, with a diameter in the range 1-2 m. The length depends on the size of the plant, may be up to 15 m. The drum is filled about 50% with liquid water, where the water at the surface is at the boiling point. The steam drum is used to separate the saturated steam and liquid phase of water mixture. It is fed with the preheated water from the Economizer and the steam/liquid mixture from the evaporator.

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[1] The numeric values are only informative, these values varies from one to another plant.

3. Evaporator (EV). The evaporator generates steam from the liquid water of the drum. It consists of one or more coils that heat the effluent (water), to the saturation point for the pressure it is flowing.
4. Superheater (SH). The superheater is used to dry the saturated steam from the steam drum. In some units this steam may only be heated to little above the saturation point where in other units it may be superheated to a significant temperature for additional energy storage. The Superheater is normally located in the hotter gas stream, upstream the evaporator. The position of the exchangers of three circuits in the chimney is defined in order to optimize the HRSG efficiency. A complete representation of the HRSG with three pressure levels and actual location of the components, is shown in Figure 7, according to [2].

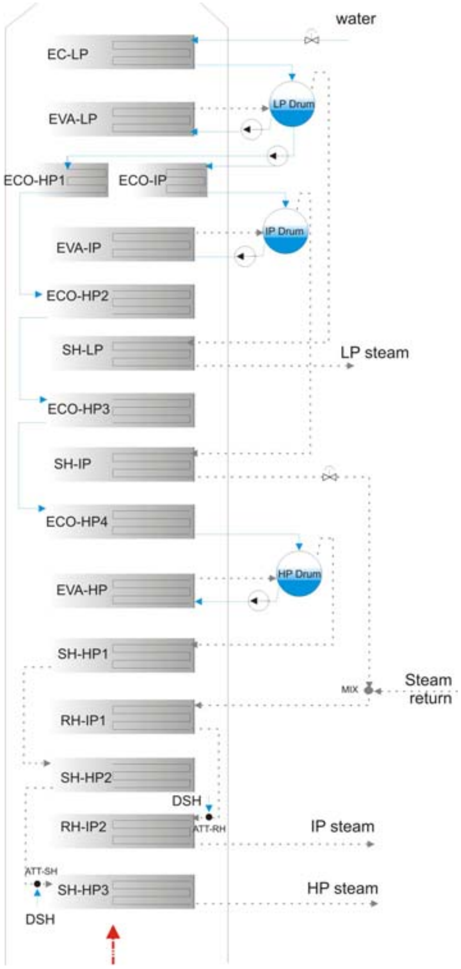

Figure 7: HRSG with three pressure levels

HRSG Circuits

In the high pressure circuit, feed water flows through three economizers (ECO-HP1, ECO-HP2 ECO-HP3), which exchange heat with the hot exhaust gases. The hot gases are flowing in the opposite direction round the circuit, gradually raising the water temperature (approx. 300°C). Then the water goes to the lower part of the HP boiler drum, and then goes naturally (by thermo pendulum phenomena) or with the help of circulating pumps through the evaporator (EV-HP). Here the water begins to transform to steam and then sinks in the top part of the drum. The steam at this point is at saturation temperature. HP steam leaves the drum via pipelines, which takes the steam to the HP superheaters (SH-HP1, SH-HP2, SH-HP3), where it is heated (approx. 200°C of superheat). The HP steam exits the superheater and passes through an attemperator (ATT-SH). Here HP feed water is injected into the steam path to control the steam temperature.

The IP and LP circuits operate similarly, however the LP circuit does not have an attemperator.

2.2.2 *Local control strategy*

High Pressure Circuit

The functional view of the HP circuit is given in Figure 8. The manipulated variables are the water flow that feeds the circuit and the desuperheating flow. The controlled variables are the HP drum level and the output steam temperature (HP steam), that is directed through pipes to the ST, to generate mechanical power. The circulation pump is used to assure a constant flow in the evaporator. In certain case, the circulation in the evaporator is done without pump by thermo pendulum phenomenon.

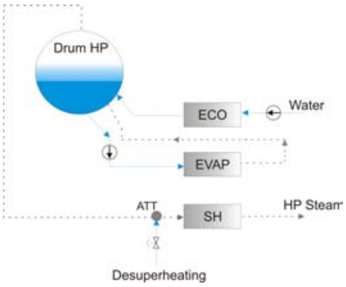

Figure 8: HP circuit

The drum level is controlled according to an input level reference signal by actuating a valve located dowstream the feedwater pump. The regulation of the HP steam temperature is performed according to an input temperature reference signal by desuperheating the corresponding steam fluxes, i.e. by injecting water upstream the inlet section of the superheater (SH).

Intermediate Pressure Circuit

The functioning of the IP circuit is similar to the above (HP circuit), the only difference is that this circuit uses steam returned from HP turbine. The exhaust steam from HP turbine is mixed with IP steam and re-heated in the HRSG (Figure 9).

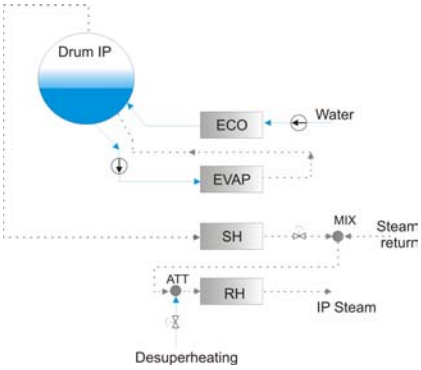

Figure 9: IP circuit

The control strategy is the same, the IP drum level is controlled according to an input level reference signal while the IP steam temperature is controlled to an input temperature reference signal, by desuperheating, by injecting water upstream the inlet section of the resuperheater (RH).

Low Pressure Circuit

The functional view of the LP circuit is shown in Figure 10. The manipulated variable is the feed water flow and the controlled variable is the drum level. The LP drum level is controlled according to a level reference signal, by actuating on the valve.

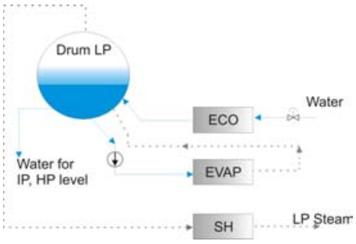

Figure 10: LP circuit

2.2.3 Physical limitations and constraints

The three circuits have the same type of physical limitations and constraints that are mainly linked to the stress of the material and the component life consumption. As the pressure and temperature are higher, these constraints are more critical for the HP and IP circuits.

High Pressure and Intermediate Pressure Circuits

The first type of constraints is related to stress, the mechanical stress that originates from internal pressure and the thermal stress that originates from thermal expansion. These constraints are specified on the pressure in pipes and/or on the gradients of temperature in superheaters and/or of pressure in drums.

The second type of constraints is related to condensation. At start-up, the steam of the drum can condense in the superheater section. It is then necessary to limit condensate formation in the colder part of the SH and to prevent slugs of condensate to be pushed into the steam pipes.

The third type of constraints is specified on the minimum flow rate in pumps. This constraint is imposed to avoid the cavitation in pumps [5] because this degrades the performance of the pump, resulting in fluctuating flow rate, discharge pressure and can also destroy pumps internal components. These constraints doesn't exist in case of natural circulation.

Low Pressure Circuit

The first type of constraints is specified on the gradient of pressure in the LP drum, this is imposed to keep the thermal stress in the allowable limits.

The second type of constraints is specified on the gas temperature. The eco inlet water temperature has to be greater than the flue gas acid dew point to avoid the gas condensation and corrosion.

The last type of constraints is specified on the minimum flow rate in pumps, to avoid the cavitation problem.

The gradients prescribed to prevent the fatigue failures, are typically determined using calculations performed in accordance with German Standard, TRD 301 or European Norm, EN 12952 ([3],[4]). As mentioned before, the critical components are the drums and high temperature superheater/reheater headers. For large steam drums with a wall thickness greater than 100 mm, operating at 100 bar and over, the acceptable temperature gradient is 3 – 6°C/min, while for smaller drums operating at 60 bar, the temperature gradient can be 8°C/min. For the superheaters with a wall thickness greater than 25 mm, the acceptable temperature gradient is up to 17°C/min.

Protection circuits

The protection circuits at the HRSG level (for all circuits HP, IP, LP) which are imposed to ensure safety operations of the system and to avoid the abnormal situations, are:

- Overtemperature: when the steam temperature exceeds the safety limit,
- High drum level: when the level is too high, the drum can give wet steam, leading to turbine blade erosion,
- Low drum level (Loss of water): when the boiler has a loss of feed water and boils dry can be extremely dangerous. If feed water is then sent into the empty boiler, the small cascade of incoming water instantly boils on contact with the superheated metal shell and leads to a violent explosion,
- Low water pressure in desuperheaters (ATT): when the water pressure injected is too low,
- Feed water flow deviation: when the flow exceeds the maximum capability limit of the feed water system,
- Overpressure: when the pressure in tubes increases over the safety border.

2.3 Steam Lines

2.3.1 Description

The steam lines are the pipes system that makes the connection between the HRSG, the ST and the condenser, thus the steam from the HRSG passes through pipes and is directed to the ST (when this is started) or to the condenser by means of the bypasses [6]. As long as the ST is not started, the steam from the HRSG is deviated to the condenser or come back to be re-heated (only HP steam). The steam line is provided with vent valve and bypass systems, dependent on the manufacturer, these pipes can have different dimensions, with a possible length of 200 m.

A functional view of the steam line is shown in Figure 11. At the start-up the objective of steam line is to avoid the sudden warming of the pipes (to limit the stress and to avoid the condensation) and to get temperature and pressure conditions of the steam (steam quality), necessary for the operation of ST. These conditions are reached by controlling the steam that is admitted inside the pipe with the evacuation and the bypass systems.

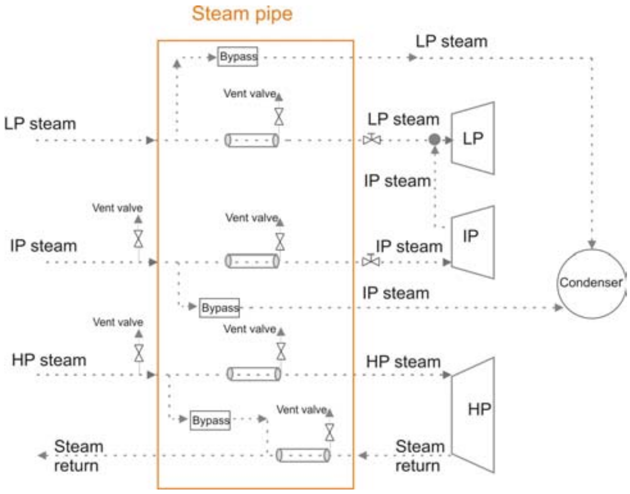

Figure 11: Steam Lines

2.3.2 *Physical limitations and constraints*

The first type of constraints refers to the gradient of increasing pressure and temperature in pipes. This constraint is imposed to limit the stress (mechanical, thermal) and automatically to minimize the components lifetime consumption.

The second type of constraints is specified on the condensation. It must avoid as possible the condensate formation and the condensate migration through pipes otherwise undesirable effects on the plant can occur.

Another type of constraints is specified on the purge flow rate. If the purge flow rate is too low, a part of condensate cannot be blown off and hence the condensation effect is not eliminated.

Relative to safety operation, the system is equipped with protection circuits to avoid the following situations:

- Overpressure : when the pressure in pipes exceeds the security limit,
- High condensate level : when the condensate level in the drain pot is too high.

2.4 Steam Turbine

2.4.1 *Description*

The Rankine cycle steam turbine transforms thermal energy from pressurized steam to mechanical power. The working fluid in a Rankine cycle follows a closed loop and is re-used constantly, unlike the Brayton cycle that is usually run as an open system. In a typical larger power stations, to maximize efficiency, the steam turbine is split into three separate stages (Figure 12), the first being the High Pressure (HP), the second the Intermediate Pressure (IP) and the third the Low Pressure (LP) stage, where high, intermediate and low describe the pressure of the steam.

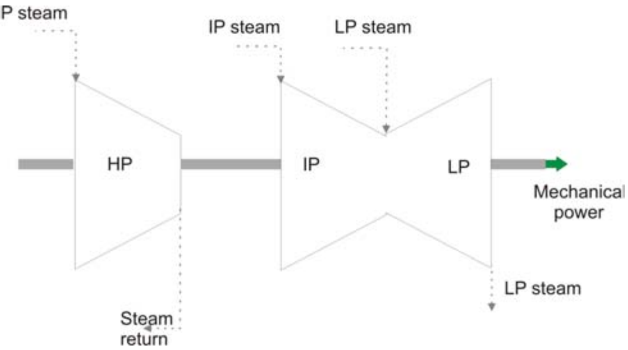

Figure 12: Steam turbine schematic

The steam from the HSRG is passed through the HP stage, it is returned to the boiler to be re-heated to its original temperature although the pressure remains greatly reduced. The reheated steam then passes through the IP stage and finally to the LP stage of the turbine. Steam enthalpy is converted into rotational energy as it passes through a turbine stage. A turbine stage consists of a stationary blade and a rotating blade. Stationary blades convert the potential energy of the steam (temperature and pressure) into kinetic energy (velocity) and direct the flow onto the rotating blades. The rotating blades convert the kinetic energy into impulse and reaction forces caused by pressure drop, which results in the rotation of the turbine shaft or rotor.

In a combined cycle system, the ST can be operated in two different modes, sliding pressure or fixed steam inlet pressure control (control valves are throttled), the combination of these operation modes depends on the level of load. During sliding pressure control, the control valves are fully open. The steam pressure is a function of the steam mass flow entering the steam turbine. The load (power output) of the steam turbine depends on the mass flow and is not directly controlled. Thereby the load on the steam turbine can only be augmented by increasing the steam flow, which, of course, involves generating more steam in the HRSG and generally requires an increase in heat from the gas turbines. Thus steam units operating in sliding pressure mode will not respond significantly to governor action in the first seconds following an event on the power system and may take a minute to several minutes to respond with an increase in power. Generally ST operates in sliding pressure mode between approx. 60% and 100% ST load. When load decreases below 60%, ST control valves are throttled to maintain the HRSG pressure at the preset minimum level of approx. 60% of the rated steam pressure (constant pressure mode).

2.4.2 Local control strategy

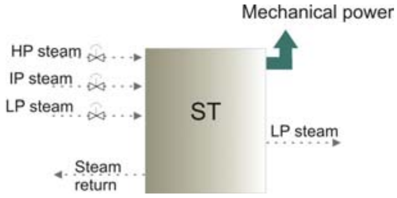

Figure 13: Steam Turbine

In Figure 13 is presented the functional view of the ST. In the fixed steam inlet pressure control, the valves allow to control the steam admission (HP, IP, LP steam) inside the stages ST. Controlling the steam flow, by actuating on the admission valves, the ST rises gradually in speed and in temperature. When the ST accepts the total HRSG steam flow, its output is not regulated anymore.

2.4.3 Physical limitations and constraints

The main limitations for a faster start-up are originated in the drastic thermal transients of the steam turbine components. Below are presented the constraints related to the ST in order to avoid the start-up if the steam quality (temperature, pressure, purity) is not good.

The first type of constraints is specified on the gradients of increasing steam temperature at admission, of increasing speed, of increasing load also on the difference between metal and steam temperatures and the difference between the static and rotating parts. Generally the acceleration of the turbine start-up leads to an increase of stresses (mechanical, thermal) in their components [7]. The longest and most limiting thermal transients are associated to components with the thickest metallic parts, more precisely, in the HP and IP steam turbine rotors and shells. In these parts, temperature increases quickly from about 90°C to 565°C during start-ups. These huge temperature swings produce two potentially hazardous effects: the development of thermal stresses and the differential expansion between rotating and static parts. Both phenomena can have catastrophic consequences if not properly handled, namely, high thermal stresses consume low cycle fatigue life in steam turbine rotors for they favor crack initiation, the acceleration of crack propagation and even fractures. Also, a large differential expansion can give rise to rubs, which in turn may lead to permanent damage and turbine performance degradation.

Another type of constraints is specified on the moisture content of steam. It is essential that the turbine to be started with dry steam, if the moisture content of steam is over the imposed limit (typically 10% moisture content), it can produce major erosion and corrosion problems. In general the steam is superheated and no moisture is present at the inlet. However, moisture can appear at the outlet particularly for the LP stage.

The third type of constraints very important for start-up is specified on the level of water purification. While the steam does not have the necessary purity, any admission into ST is not possible.

The fourth type of constraints is specified on the steam exhaust from LP stage. The steam pressure which goes out of the turbine has to be limited, so that to avoid the mechanical stress.

Relative to the abnormal situations and safety operation, which could lead to shut down of the plant, the system provides protection circuits during the following events:

- Overspeed: when the rotating speed of the turbine is too high, that can occur when the torque generated by the steam flow exceeds the countertorque generated by the load,
- HP exhaust steam temperature: when the exhaust steam temperature (steam return) is too high,
- LP exhaust steam temperature: when the exhaust steam temperature is too high,
- Water ingress to blade: when the moisture content of steam is over the safety limit (a limit is set at about 10% moisture content, 90% steam quality),
- HP turbine proportional pressure: when the pressure is too low,
- Turbine bearing temperature: when the temperature inside the turbine is too high,
- High turbine exhaust pressure (low condenser vacuum): when the turbine exhaust pressure is high, the last stage of the blades in the low-pressure (LP) turbine will become overheated and damaged.

2.5 Condenser

2.5.1 *Description*

The condenser is a device that converts steam into liquid. Once the steam has passed through the steam turbine, it enters the condenser where heat is removed until it condenses back into liquid water. This is done by passing the wet steam around thousands of small cold water tubes. The condensed steam is collected at the bottom of the condenser and returned to the HRSG using extraction water pumps, to begin the water-to-steam, steam-to-water cycle again.

2.5.2 *Local control strategy*

The functional view of the condenser is given in Figure 14. The manipulated variables are the water flow, the desuperheating flow and the vacuum pump. The controlled variables are the steam temperature, the vacuum pressure and the condenser level.

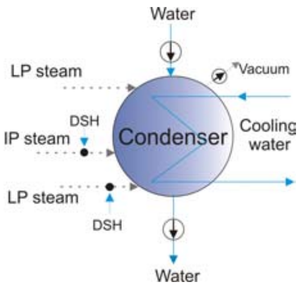

Figure 14: Condenser

The condenser level is controlled according to an input level reference signal, controlling the water inflow, i.e. by actuating on the water pump. The regulation of the steam temperature is performed according to an input temperature reference signal by desuperheating the corresponding steam fluxes, i.e. by injecting water upstream the inlet section of the condenser. This regulation is active at start-up when the bypasses (see Steam lines) are used. The vacuum pressure is controlled by actuating the vacuum pump, according to an input reference signal.

2.5.3 *Physical limitations and constraints*

The main constraint is specified on the level of liquid water, to avoid the cavitation in pumps. The system disposes of protection circuits to avoid the following situations:

- High condenser pressure: when the pressure in condenser exceeds the security limits,
- High condenser temperature: when the temperature exceeds the safety limits,
- Low water pressure in desuperheaters (DSH): when the water pressure injected is too low,
- Water level: when the condenser level exceeds the allowable limits (when the level is too high or too low).

3 Objective specification

CCPP start-up optimization aims the following objectives, while respecting the constraints.

Minimization of the start-up time.

Minimizing the start-up time is a crucial competitive advantage in a liberalized market since it is desirable to propose the smallest starting time among all energy providers. The optimization will find the control sequence that minimizes ΔT, the time necessary to go the system from the initial state to the final state.

$$J1=\int_{to}^{tf} dt = \Delta T \qquad (1)$$

where to and tf are the initial time and the final time respectively. tf depends on the control inputs by a dynamic equations.

Minimization of the operating costs.

Start-up costs include costs for fuel or other consumables like water and chemicals. A reduction of the fuel consumption or water means a direct increase of the customer value. Cost reductions are accomplished by minimizing J2.

$$J2=\int_{to}^{tf} Ec\, dt - \int_{to}^{tf} Ep\, dt \qquad (2)$$

where Ec represents the energy consumed and Ep the energy produced. The term (2) can be rewritten as:

$$J2=\int_{to}^{tf} Crm\, dt - \int_{to}^{tf} E\, dt \qquad (2')$$

where Crm is the raw material cost and E is the benefits of selling electrical power.

Minimization of the material wear.

This minimization has two main benefits:

- reduce the plant life-time consumption,
- reduce the number of maintenance stops.

In this control problem the goal is to reduce the material wear (thermal stress, mechanical stress) as much as possible, that is to minimize J3.

$$J3=\int_{to}^{tf} Mw\ dt \qquad (3)$$

where Mw is the material wear.

Minimization of the environmental impacts.

The reduction of pollutant emissions has a major importance in view of the constantly increasing restrictions on the environmental impact by law. The high temperature in the combustion zone (approx. 1350°C) results in the nitrogen in the air combining with oxygen, also additional nitrogen could be present in the fuel; consequently the combustion temperature and the NOx concentrations have to be limited. The goal is to keep the gas emission as low as possible, by minimizing J4.

$$J4=\int_{to}^{tf} Gem\ dt \qquad (5)$$

where Gem represent the quantity of gas emissions (NOx, CO2).

Minimization of the start-up failure.

This is an important point since a missed start means time lost and there is the possibility that the system does not respond to the request issued from dispatching. This goal can not be easily associated with a criterion as previously. To minimize the risk of start-up failure, a analysis must be done to determine the main causes (model error, sensor error, ...) and choose a criterion that increase the robustness of the control for this causes.

The objectives presented above must be considered all together and can't be considered separately; it is obvious that a fast start-up will lead to a higher wear of materials than a slow start-up will. For that, a compromise between a fast start-up and the other objectives has to be made, in such a way that the controller respects the imposed constraints.

4 Robustness specification

The robustness is an important issue in control design and is important to assess the performance analysis. For a combined cycle power plant the large changes in plant dynamics require a robust controller.

Generally the techniques of predictive control are robust and keep the system performances supposing that the mathematical model of the plant is not represented with a high level of detail and accuracy. The model used must be able to represent the behavior of the plant (all the start-up phases, turbines start-up, boiler start-up, load up, etc.), but there is not practically a mathematical model that can represent exactly the real plant. Therefore the implementation of the control law on the real plant, can lead to performances quite different from those imposed in design. This fact is due to the difference between the real plant and the model used during the design phase (modeling errors).

The HD-MPC solution must be robust at:

- Modeling errors and/or model simplifications. These errors bring in the process modeling, uncertainties, which can influence the system performances in a negative way. The neglected phenomena or dynamics can be a source of uncertainty.
- Modification of the system parameters. The phenomena that have to be considered are:
    - For the GT, the modifications of the fuel or/and air characteristics, the fouling of compressor blades.
    - For the HRSG, the fouling of heat exchangers, of the valves.
    - For the Steam Line, the fouling of pipes.
    - For the Steam turbine, the evolution of the throttle characteristics.

5 Control architecture

In this section, from the global representation of the plant (Figure 15), we make a suggestion of hierarchical control architecture for CCPP.

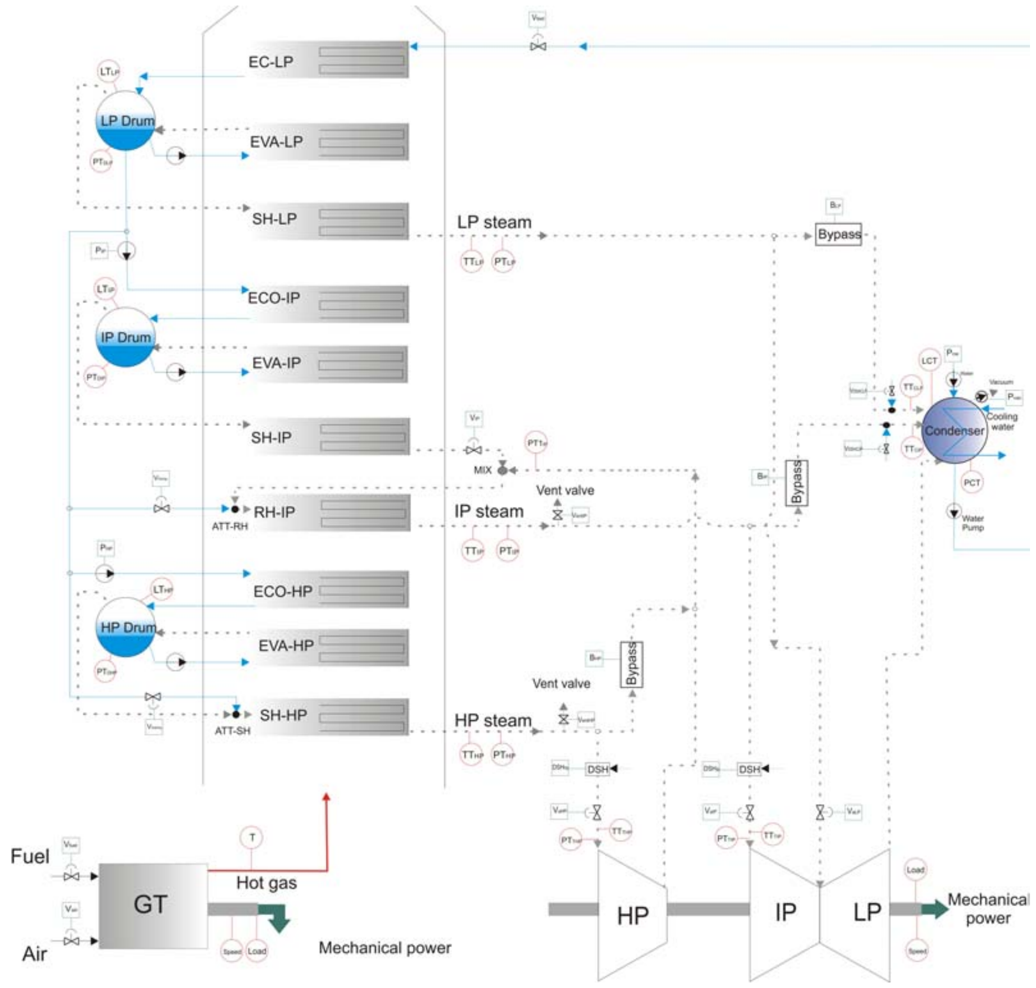

Figure 15: Overall scheme of CCPP

A possible architecture is illustrated in Figure 16 and Figure 16. It consists of 3 layers:

- The upper level - Global coordinator - coordinates the components of the plant (GT, HRSG, ST and Condenser) - this level addresses strategic economic requirements and does not necessarily take into account the dynamic characteristics of the plant,
- The intermediate level (High Pressure Control (HPC), Intermediate Pressure Control (IPC), Low Pressure Control (LPC)), this level observes and controls some part units that consists of the process itself and the local regulators,
- The low level (Temperature Control (TC), Pressure Control (PC), Level Control (LC)) - this level observes and controls the process itself.

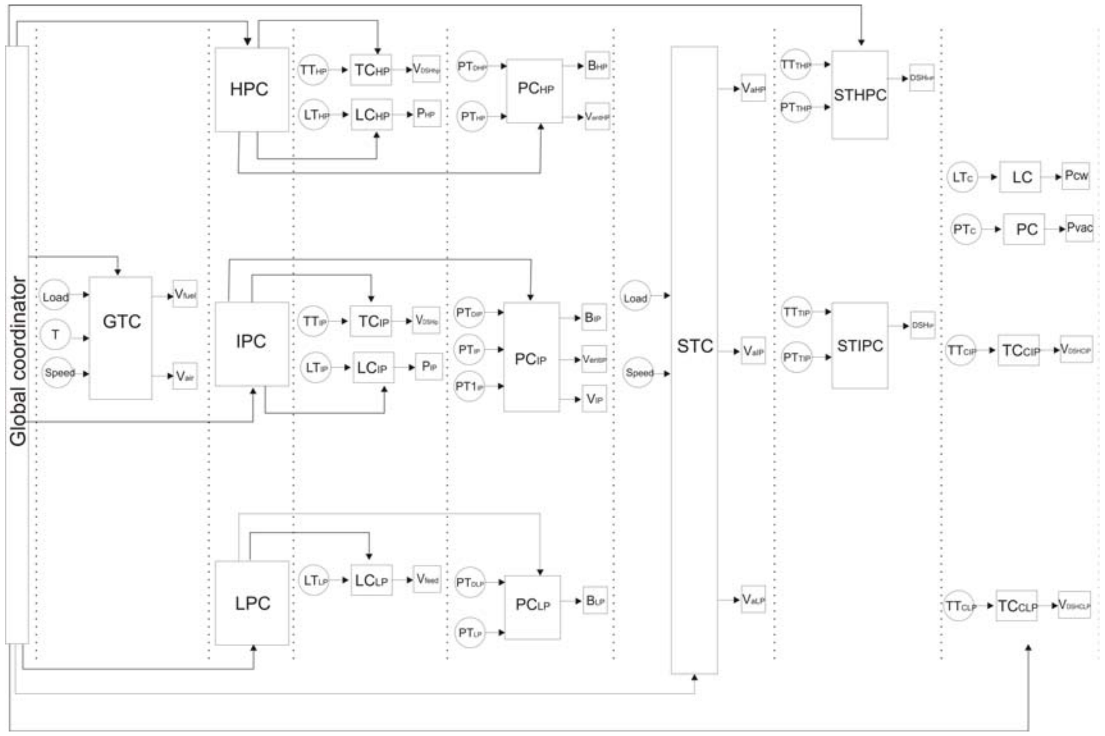

Figure 16: Control Architecture of the CCPP

High Pressure Controller (HPC) is an upper dynamic control layer above the low level control loops:

- HP temperature control (TC_{HP}) - the HP steam temperature is controlled actuating on the desuperheater valve (V_{DSHhp}) according to difference between the reference signal from the HPC and the temperature transmitter signal (TT_{HP}),
- HP level control (LC_{HP}) - the HP drum level is controlled actuating on the HP feed pump (P_{HP}) or the opening of the feedwater valve located downstream the pump, based on water level in drum (level transmitter HP - LT_{HP}),
- HP pressure control (PC_{HP}) - the HP steam pressure is controlled actuating on the vent valve (V_{ventHP}) and on the Bypass (BH_{P}) according to the pressure transmitter in drum (PT_{DHP}), the pressure transmitter in pipes (PT_{HP}) and the reference signals from the HPC.

Intermediate Pressure Controller (IPC) is an upper dynamic control layer above the low level, including the same control loops, the only difference is that the pressure control loop IP uses an additional valve (V_{IP}) and a pressure transmitter ($PT1_{IP}$) to control the steam pressure returned from HP turbine.

Low Pressure Control (LPC) observes and controls the local loops:

- LP level control (LC_{LP}) - the LP drum level is controlled actuating on the feed valve (V_{feed}), based on water level in drum (level transmitter LP - LT_{LP}),
- LP pressure control (PC_{LP}) - the LP steam pressure is controlled actuating on the Bypass (B_{LP}) according to the pressure transmitter in drum (PT_{DLP}), the pressure transmitter in pipes (PT_{LP}) and the reference signals from the LPC.

Generally GT and ST controls are defined by the vendor and cannot be changed. Gas Turbine Control (GTC) - the Speed, gas Temperature and Load are controlled by actuating on the air valve (V_{air}) and respectively the fuel valve (V_{fuel}). Steam Turbine Control (STC) - the Speed and Load are controlled actuating on the inlet valves (V_{aHP}, V_{aIP}, V_{aLP}).

At the start-up, the ST needs steam temperatures at a certain value above metal temperature, the Steam Turbine High Pressure Control (STHPC) and Steam Turbine Intermediate Pressure Control (STIPC) use the information about the steam temperature and pressure at admission, provided by the transmitters (PT_{THP}, PT_{TIP} TT_{THP}, TT_{TIP}) to control steam temperature by actuating on the desuperheatears (DSH_{HP} and DSH_{IP}).

For Condenser, the local control loops are :

- Level control (LC) - the Condenser level is controlled actuating on the water pump (P_{cw}), based on the water level in the condenser (level transmitter condenser - LT_C),
- Pressure control (PC) - the pressure in the condenser is controlled actuating on the vacuum pump (P_{vac}) according to the pressure transmitter (PT_C) and the reference signal,
- Temperature controls (TC_{CIP}, TC_{CLP}) - the IP and LP steam temperature are controlled actuating on the desuperheater valves (V_{DSHCIP}} and V_{DSHCLP}) according to the information provided by the transmitters (TT_{CIP}, TT_{CLP}) and the reference signals.

The hierarchical control architecture proposed for the CCPP is shown in another form in Figure 17. At the intermediate level, the controllers (HPC, IPC) can be MPC and for low level controllers (TC, PC, LC), the classical PID regulators. A similar architecture is proposed by [8], that uses a decentralised GPC control to optimize the power plant dynamic operating point transitions by manipulation of the low level PID controller set points.

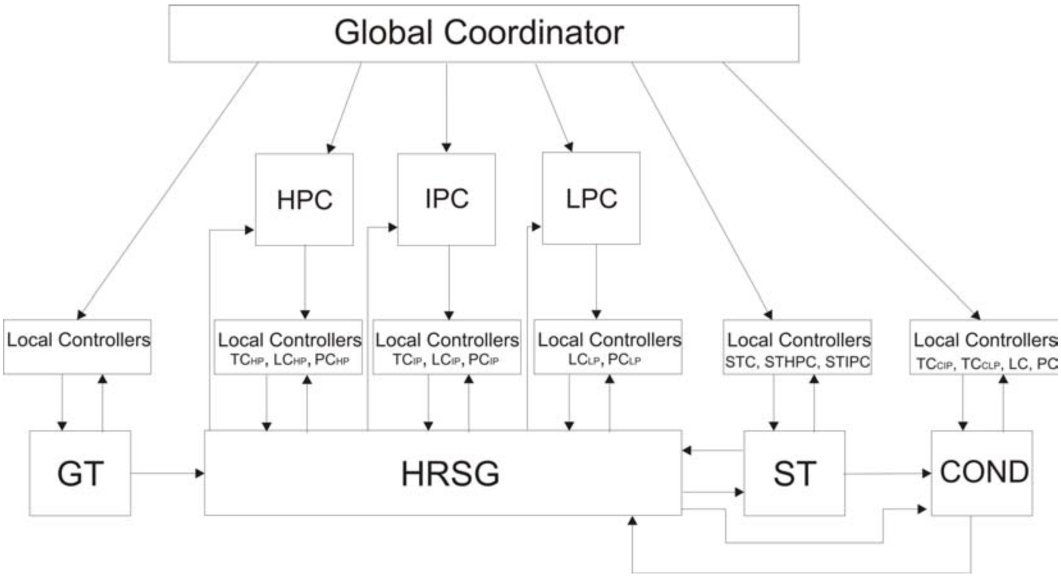

Figure 17: Hierarchical Control Architecture

6 The start-up sequence

The CCPP start-up process that will be considered in the project[2] begins when GT is started and finishes when the plant achieves the desired power output. During this start-up process the constraints that are presented above have to be respected. The aim of the control is mainly to reduce the start-up time while keeping the life-consumption of the components at a low level.

The start-up procedure is decomposed into four stages (Figure 18) that correspond to different objectives and active constraints:

1. Preparation phase: this first stage prepare the ignition of the GT;
2. HRSG Start-Up phase: the aim of this phase is to start the HRSG in order that the characteristics of the steam (temperature, pressure, content) become suitable to the admission in the ST;
3. ST Start-Up phase: during the third stage the ST is started by admitting steam;
4. Increasing Load phase: during the last stage the load of the plant is increased to its expected level.

6.1 Preparation phase

During this stage, the GT is started and the plant is purged to ensure a non-flammable atmosphere in the turbine and HRSG, prior to ignition. Purging is usually carried out by speeding-up and holding the gas turbine at ignition speed (approx. 25-30 % of nominal speed) with an engine or a similar starting equipment, until a specified number of air changes occur in the HRSG and GT. The exhaust purge from

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[2] Several actions are in fact undertaken before the GT start, like the cooling system, extraction and feed-water pumps circuits, etc. These actions are supposed to be done.

the GT is close to ambient temperature and if this enters a hot HRSG, it will cool off the HRSG.

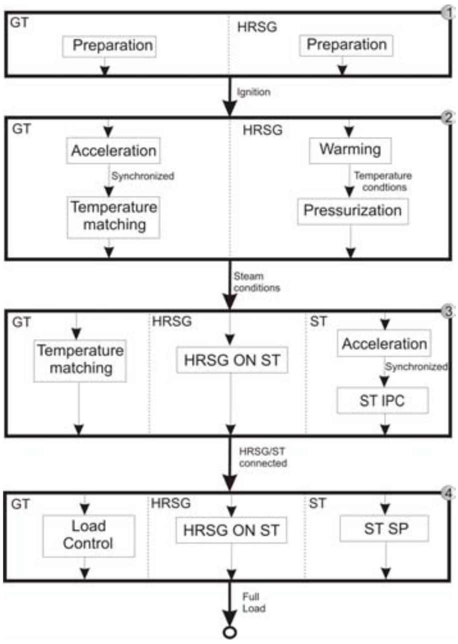

Figure 18: Start-up decomposition

Steam can actually condense in the superheater, causing stress in this section. Any condensate produced in the superheater section must be drained to prevent slugs of condensate being pushed into the steam pipes.

During this phase, the drums level control is activated to mitigate the swell effect that can appear when the GT is fired and kept active until the end of the start-up sequence.

The first constraint that the control system has to respect is on the feed water flow (minimum flow rate)[3]. When the purge is completed and the level in drums reaches the reference value, this stage is finished by firing the GT.

6.2 HRSG Start-Up phase

The second stage begins with the ignition, the GT is then accelerated (Acceleration mode) and synchronized to the grid. After synchronization the GT switches to Temperature matching, the exhaust gas temperature is controlled to gradually warm up the HRSG metal (Warming mode). When the metal temperature of the HRSG is higher than the saturated steam temperature (temperature conditions), the HRSG goes to the Pressurization mode.

In order to obtain characteristics of the steam (temperature, pressure, content) necessary to ST start-up while warming the steam lines, the pressure regulation (via bypasses and vent system) and steam temperature regulation (output HP, IP circuits, via desuperheating) begin. With the HRSG start-up phase, other constraints become active, that are relative to:

- gas temperature,
- the gradient of increasing gas temperature,
- the gradient of increasing temperature in superheaters (HP, IP),
- the gradient of increasing pressure in drums (HP, IP, LP),
- the condensation,
- the pressure in pipes.

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[3] In this text we consider that, when a constraint is activated, it remains active during the following stages of the start-up sequence.

When the steam conditions (pressure, temperature, quality) for ST start-up are fulfilled, the system goes to the third phase. These conditions depend of the temperature inside the IP stage.

6.3 Start-Up phase

During this stage, the GT is on Temperature matching mode and the HRSG is ready to start the ST (HRSG ON ST mode). The control of the gas temperature, steam pressure, steam temperature and drum level is maintained. The steam is gradually admitted in the ST, that is started. The ST starts with admission in the IP stage and when the HP steam reaches the required temperature limit, it is admitted in the HP stage. The steam admission control has to respect also the new constraints on:

- the gradient of increasing speed before synchronization to the grid,
- the gradient of increasing load,
- the gradient of increasing steam temperature at admission,
- the difference of temperature between metal and steam,
- the difference of temperature between static and rotating parts,
- the steam quality (moisture content of steam, water purity),
- the pressure steam from LP exhaust stage.
- the pressure steam at the HP exhaust.

Then the ST is accelerated (Acceleration mode) and synchronized to the electrical power grid. After synchronization the ST begins to load (fixed steam inlet pressure control mode, ST PC, steam turbine control valves are throttled to keep the steam pressure constant at the preset minimum pressure required by the HRSG). The system goes to the next step when the connection between the HRSG and the ST is complete (the bypasses are closed and the admission valves are full-opened).

6.4 Increasing Load phase

In this phase the HRSG is on the “HRSG ON ST” mode and the GT loads up to full load in “Load control” mode, where the load is controlled. A new constraint that has to be respected is on the gradient of increasing load. The ST follows the GT with increasing steam production, without regulation of its output flow (ST switches to the sliding pressure mode “ST SP”, the steam is fully admitted into the turbine). The start-up procedure is finished when the power plant work at full power.

In addition to the active constraints for each step the system control has to avoid violation of the design limits.

7 Related Work

In the last years, several studies deal with the modeling and simulation of fast start-up transients of a CCPP. For example, Albanesi *et al*. proposes the optimization of the start-up procedure using a model-based approach [9]. An optimal design method is proposed by Shirakawa *et al*. [10], the method consists in combination between dynamic simulation and nonlinear programming. Another concept is suggested by Casella and Pretolani, that study the optimization by means of the Modelica simulator [11] and Alobaid *et al*. by using the commercial software APROS (Advanced Process Simulation)[12].

A feature of the CCPP start-up problem is the relatively long delay between changes in the loading rates and their effects on turbine stress. The implementation of Model Predictive Control (MPC) techniques ([13],[14]) improve system performance, in comparison with the control conventional strategies, due to its ability to handle constraints explicitly and its prediction capability. A MPC controller to minimize CCPP start-up has been developed and tested in the real power plant [15].

The main benefits of shorter start-up were the reduction of operating costs and environmental impact, due to lower fuel consumption and to lower emissions.

In current industrial practice, thermal stresses are calculated from differential temperature measurements. A method of on-line thermal stress estimation was performed, by using mathematical models of the critical thick-walled components [16].

8 Conclusion

This paper draws an overview about the functional description of the components of a combined cycle power plants and the local control strategies; it furnishes information about the main constraints that can occur during the start-up. The start-up process is a complex task including several limitations that have to be fulfilled simultaneously. The CCPP start-up optimization can have several purposes: to reduce the start-up time, to reduce operating costs, to reduce the probability of occurrence of missed starts, to reduce the equipment ageing etc. Definitely it is not possible to achieve these requirements conjunctly. Fast start-up is an essential feature to ensure economic success in a liberalized market. It is obvious that a fast start-up will lead to more important thermo mechanical solicitation of materials than a slow start. A compromise, between a fast start-up and other objectives (like life-time consumption, water and fuel consumption), has to be made, in such a way that the controller respects the imposed constraints. The most methods available until now run offline and they need further developments to be capable of attaining similar performance in real time and in the presence of uncertainty.

The next step for the combined cycle application is to develop a model that represents the objective function and the constraints. A mathematical formulation of the start-up problem has to be done and has to be decomposed in smaller problems. The decomposition is not trivial and must not necessarily follow the material partition used in this report, for instance [17] proposed to decompose the startup sequence in several steps that will be optimized separately. So the plant optimizer can be seen as a finite state machine itself. For each state, a specific and thus simpler model can be used. Cascade decomposition with slow and fast dynamics models can also be applied. As the objective function is the start-up time, price decomposition technique or other solution based on the hypothesis of the additivity of the cost function doesn't seem to be applicable directly. Other solutions should probably be proposed to address the decomposition of the minimum time optimization problem.

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