Study of Steam Export Transients in a Combined Cycle Power Plant

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Abstract

A Combined Cycle Power Plant incorporates a cogeneration system which supplies steam to a nearby industry. Because of the contractual need to ensure the supply of steam to industry, the Combined Cycle Steam Export System is connected to two auxiliary boilers which will operate when the cycle is not available.
Using EcosimPro, we have studied the transients produced in the face of uncontrolled events which could give rise to an interruption in the supply. The purpose of the study is to verify the suitability of the control system and determine the initial load of the auxiliary boilers which guarantees the continuity of steam supply.

Key Words: Steam transients, cogeneration, EcosimPro, combined cycles, control systems.

1 INTRODUCTION

A Combined Cycle basically comprises three components: a gas turbine, a heat recovery steam generator and a steam turbine. The gas turbine burns natural gas to generate electrical power. The gas turbine exhaust gas is routed to a heat exchanger which is commonly known as the heat recovery steam generator. Here the residual heat from the exhaust gas is used to heat the water and generate steam which is expanded in the steam turbine, increasing the overall production of electrical energy.

The Combined Cycle under study comprises a heat recovery steam generator with three pressure levels, each formed by an evaporator, a pressure drum and a superheater. The main steam from the high pressure superheater expands in a high pressure section of the steam turbine. As it leaves, the cold reheat steam is combined with the steam from the medium pressure superheater and the mix enters the reheating area of the heat recovery steam generator. This hot reheat steam is then fed into the medium pressure turbine. The steam produced from the second expansion is combined with the steam from the low pressure superheater and this mix is routed into the low pressure section of the turbine and then discharged to the condenser.

A Combined Cycle Power Plant can produce 390 MW of electrical power when all the steam produced in the heat recovery steam generator is passed through the turbine. If part of the steam generated is exported, the electrical power decreases to 350 MW for a maximum of 150 t/h export steam. The greater part of this quantity (66 t/h) is consumed by a single nearby industry. Table 1 contains the series of pressure and temperature requirements that the export steam must fulfil at the point of delivery:

Table 1: Export Steam Conditions

Parameter	Minimum	Average	Maximum
Pressure (barg)	23	25	30
Temperature (ºC)	230	234	243
Present flow	—	20	45
Future flow	—	41	66

There are three possible sources of export steam: main steam, cold reheat steam and medium pressure steam. The source used depends on the steam flow exported and the cycle load used. Selection of the source to feed the supply is based on a pressure criterion.

The transient states produced in the system can be attributed to two different causes. They may be due to changes in the conditions of the cycle such as a unit trip, load rejection, transfer to the auxiliary boilers, etc; or they may be due to variations in the demand for export steam. Of all the possible cases, those which are most significant have been chosen for the study because of their effect on the operating conditions of the cycle The main purpose of the study is to establish for each plant operating state, auxiliary boiler load levels and control system parameters that guarantee a continuous supply of export steam under the specified pressure and temperature conditions.

2 SYSTEM DESCRIPTION

2.1 EXTRACTION STEAM

As indicated previously, combined cycle export steam can come from three different sources:

- Main steam
- Cold reheat steam
- Medium pressure steam

All three supplies have some components in common which prevent the backflow of steam, such as the isolation valves at the inlet of each of the lines and the non-return valves.

The main steam extraction is located at the outlet of the high pressure superheater. During normal cycle operation, the steam flow from the high pressure superheater is divided and routed to the high pressure turbine and the process steam extraction.

The main steam pressure and temperature are controlled by means of throttling and attemperation with feedwater so that they match the conditions of the cold reheat steam.

The cold reheat steam is extracted at the high pressure turbine outlet upstream of the inlet to the reheater without any adjustment to its thermal characteristics. Lastly, the intermediate pressure extraction steam is obtained at the outlet of the intermediate pressure superheater, downstream of the bypass connection, and is subjected only to pressure adjustment.

The steam from all three sources is routed to the process steam export header. The conditions of the steam in this line are adjusted to those required by the process. The adjustment is made in two stages; namely, pressure regulation and attemperation with feedwater.

Lastly, the pipe which carries the steam to its final destination is connected inside the header. A connection is made in this line to the auxiliary boilers.

2.2 AUXILIARY BOILERS

The facility is equipped with two auxiliary boilers, each with a capacity to produce a maximum of 75 t/h. They are designed to guarantee the supply of process steam without transients which give rise to loss of supply in the event of unit trip or other combined cycle unavailability.

The auxiliary boilers have a dual control system which can be used depending on whether or not the cycle is exporting steam.

The auxiliary boiler startup curve is a datum provided by the manufacturer.

It must be borne in mind that operation of the auxiliary boilers below their maximum technical output (approximately 20 t/h) cannot be guaranteed.

2.3 EXTRACTION STEAM CONTROL SYSTEM

During normal operation, the combined cycle control system changes from one steam source to another depending on the cycle load level and steam export flow. When demand increases, steam is introduced from a source with higher pressure until the steam from the lower pressure source is replaced. This replacement is automatic, maintaining the pressure upstream of the steam export control valve.

The possible extraction modes from the different sources are as follows:

- Cold reheat steam (CRH)
- Main steam and intermediate pressure steam (HP+IP)
- Main steam (HP)

The Extraction Steam Flow Map (Figure 1) illustrates the different operating modes expected, depending on the cycle load level and the demand for process steam.

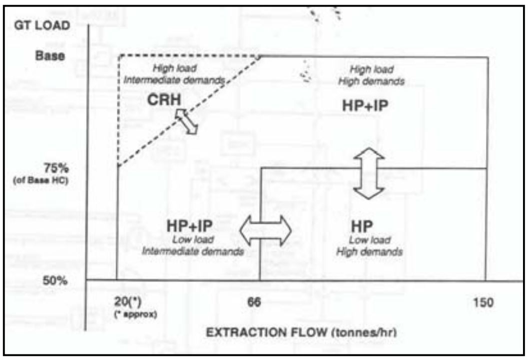


Figure 1

3 DESCRIPTION OF THE MODEL

The steam export transients have been simulated with a model built with EcosimPro. The model incorporates the following components:

- Boundary conditions
- Pipes
- Control valves
- Non-return valves
- Attemperators
- PI controllers

- Pressure sensors
- Auxiliary boilers

There are two types of ports which connect the different components: fluid ports whose variables are pressure, temperature and flow; and control ports whose variables are analogue signals.

The model built with EcosimPro is depicted in Figure 2.

The limits of the model are as follows:

a. Input
   - Outlet from the high pressure superheater
   - Outlet from the intermediate pressure superheater
   - Cold reheat steam outlet

b. Output
   - Steam export supply
   - Connection to other consumers
   - Main steam entering the turbine

3.1 BOUNDARY CONDITIONS

There are two types of boundary conditions:

- Capacitive: where the flow, the pressure and the temperature are specified
- Resistive: where the pressure and the enthalpy are specified

The boundary conditions have to be defined for each one of the model limits. In the case of high and medium pressure extraction steam and cold reheat steam, these conditions are the pressure and enthalpy; for the remaining limits (export steam supply, supply to other consumers, main steam to the turbine) the pressure, temperature and flow of each point have to be specified.

3.2 PIPES

The equations which represent the behaviour of the pipes include the effects of load loss due to friction and the storage of steam inside them. Additionally, the thermal capacity of the metal is also taken into account. although the exchange of heat between the metal and the outside is not considered because all the pipes are insulated.

Each pipe is considered divided into a number of equal elements, alternating resistive elements (pressurisers, type R) and capacitive elements (mass accumulators, accumulators, type S). The number of elements depends on the volume of the pipe and the precision required. As a general rule there is just one resistive element and one capacitive element for each pipe, except for the connecting line with the industrial consumer (some 200 m in length) which is divided into ten elements. In addition, we avoid joining two elements of the same type to prevent the generation of algebraic loops in the equation system resolution.

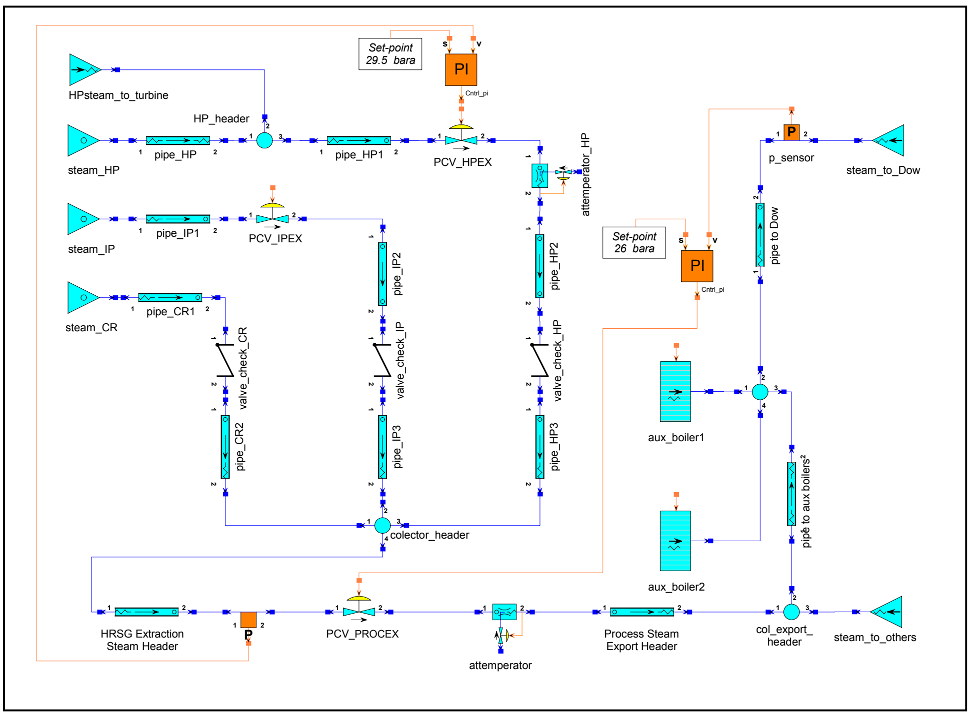
Each pipe element must comply with the mass and energy conservation principles:

$$V \frac{d\rho}{dt} = \dot{m}_{in} - \dot{m}_{out} \qquad (1)$$

$$\frac{dU}{dt} = q_{in} - q_{out} - q_{pared} \qquad (2)$$

where:

V is the volume of the pipe element
ρ is the density
$\dot{m}$ is the inlet or outlet flow of the element considered
q is the energy that enters or leaves the element, and it is calculated by multiplying the inlet or outlet flow by the average



enthalpy in that element
U is the internal energy of the pipe element

Heat transfer between the pipe and the steam is calculated with formula 3:

$$q_{pared} = h_c \cdot \left(T_v - T_{pared}\right) \cdot A_{pared} \qquad (3)$$

where:

h_c is the coefficient of heat exchange due to convection, calculated using the Petukhov formula [Reference 1]
T_v is the temperature of the steam
T_{pared} is the temperature of the inner surface of the pipe
A_{pared} is the inner surface area of the pipe element

The evolution over time of the internal temperature of the metal is determined by equation 4:

$$\frac{dT_{pared}}{dt} = \frac{q_{pared}}{M_{pared} \cdot c_{P\ pared}} \qquad (4)$$

where:

M_{pared} is the mass of the pipe element
$c_{P\ pared}$ is the specific heat of the metal

Using the mass and energy conservation equations for each pipe element (equations 1 and 2) based on the pressure and the enthalpy and the operand, we obtain:

$$P' = \frac{\left(\rho + \left.\frac{d\rho}{dh}\right|_P h\right)\left(\dot{m}_{in} - \dot{m}_{out}\right) - \left.\frac{d\rho}{dh}\right|_P \left(q_{in} - q_{out} - q_{pared}\right)}{V\left(\rho \left.\frac{d\rho}{dP}\right|_h + \left.\frac{d\rho}{dh}\right|_P\right)}$$

(6)

$$h' = \frac{\left(\frac{\dot{m}_{in} - \dot{m}_{out}}{V}\right) - \left.\frac{d\rho}{dP}\right|_h P'}{\left.\frac{d\rho}{dh}\right|_P} \qquad (7)$$

where:

P is the pressure of the steam
h is the enthalpy
P' is the derivative of the pressure with respect to time
h' is the derivative of the enthalpy with respect to time
$\left.\frac{d\rho}{dh}\right|_P$ is the derivative of the density with respect to the enthalpy at constant pressure

$\left.\frac{d\rho}{dP}\right|_h$ is the derivative of the density with respect to the pressure at constant enthalpy

The pressure drop in each pipe element is a function of the geometry and of the frictin coefficient K and is calculated with the following formula:

$$\frac{l}{A} \cdot \dot{m}' = \left(P_{in} + av_{in}\right) - \left(P_{out} + av_{out}\right) - K \frac{\dot{m}^2}{2\rho A^2} \qquad (8)$$

where:

l is the length of the pipe element
$\dot{m}$ is the steam flow
P is the inlet or outlet pressure
av is the artificial viscosity
A is the pipe section
ρ is the density

3.3 CONTROL VALVES

There are three pressure control valves; two are located in the high and intermediate pressure extraction steam headers (PCV_HPEX and PCV_IPEX) and the other in the process steam export header (PCV_PROCEX). Using the model built with EcosimPro and based on the most unfavourable steady state conditions, the capacity and type of the valves have been calculated (see Table 2). Thus the valves PCV_PROCEX and PCV_HPEX are of the isopercentage type, while the valve PCV_IPEX is of the linear type.

On the other hand, an actuator has been incorporated into each valve which provides the opening times summarised in Table 2:

Table 2: Control Valve Characteristics

Valve	Size	Cv	Opening
PCV_PROCEX	10”	1260	5 s
PCV_IPEX	6”	400	2.5 s
PCV_HEX	8”	875	7 s

Valves PCV_PROCEX and PCV_HPEX are positioned in accordance with the signals received by their PI controllers to maintain pressure at the industrial supply point and in the header top of the process steam export header, respectively. The position of valve PCV_IPEX is a boundary condition since its opening is controlled to maintain pressure in the intermediate pressure drum, which is not included in the model.

Control valve operation is modelled in accordance with Reference 2.

3.4 HEADER

The component denominated header is used to connect the different elements. It is equivalent to an S type element except that it can have several inputs and outputs and it does not incorporate load loss.

The model includes four headers:

- HP_header component: this is located at the high pressure extraction steam inlet and it divides the flow into two parts; one part is routed to the turbine and the other part to the process steam export header

- colector_header component: this represents the connection of the three extraction steam lines in the header top of the header

- col_export_header component: this is located at the end of the header and comprises one inlet from the header and two outlets, one to the steam export pipe and the other to future consumers

- col_aux_boiler component: this is located in the steam export pipe and represents the connection of this line with the line from the auxiliary boilers

3.5 ATTEMPERATORS

The system is equipped with two attemperators, one located in the high pressure extraction steam header and the other in the process steam export header. Both are positioned downstream of the associated pressure control valve.

Each attemperator comprises the following components:

- Water flow control valve
- Temperature sensor downstream of the attemperator
- PI controller
- Header

The set-points of the high pressure attemperators and the process steam export header are 420ºC and 240ºC, respectively.

3.6 AUXILIARY BOILERS

The auxiliary boilers are controlled in two different ways: there is flow control in the discharge of the boilers and pressure control at the point of steam export supply.

When the combined cycle is exporting steam, the auxiliary boilers are producing a constant flow of steam commensurate with the load and demand. However, when the auxiliary boilers are supplying all the export steam, they control the supply pressure.

When there is a trip in the combined cylce, the auxiliary boilers automatically begin to increase their load to the steam level that existed prior to the trip. During this process, the combined cycle has to maintain the supply pressure until valve PCV_PROCEX has completely closed or until the auxiliary boilers have reached the required steam level.

The EcosimPro model of the auxiliary boilers includes the following components:

- Boundary condition of the capacitive type, where the pressure and enthalpy are established
- Control valve
- Valve actuator
- Flow sensor
- PI flow controller
- Valve actuator control signal selector
- Input signal delay to the header

Signal delay simulates the delay between the firing signal and steam production in the boiler.

3.7 NON-RETURN VALVES

The components which represent the non-return valves prevent the backflow of steam during transients and changes in all operating modes. Their formulation includes the corresponding load loss.

4 TRANSIENT ANALYSIS CASES

Among the transients which can give rise to variations in steam export operation are those produced by the transfer of supply between the auxiliary boilers and the combined cycle, load rejection, an increase or reduction in the cycle load, etc.

From the point of view of guaranteeing the supply of export steam, only the transients unleashed by uncontrolled events are of interest; fundamentally, combined cycle trip and sudden variations in steam export demand.

4.1 COMBINED CYCLE TRIP

All the cases studied are based on an initial combined cycle steady state corresponding to the values established in the heat balances. After 300 seconds have elapsed, the unit trips and the steam accumulated in the pipes, superheaters and high pressure drum is routed to the process steam export header.

The moment the trip occurs, the command is given to start one or both auxiliary boilers to cover the demand for steam. Throughout the duration of startup, the residual heat from the heat recovery steam generator is used to continue generating steam at a progressively lower pressure and temperature. The evolution of this pressure and temperature is a datum supplied by the boiler manufacturer.

When the supply pressure cannot be maintained within the limits specified in section 1, additional transients are calculated with initial states different from those of the auxiliary boilers in order to determine the minimum initial load of the boiler which will enable the supply pressure to be maintained.

4.2 VARIATION IN EXPORT STEAM DEMAND

As in previous cases, this case is based on an initial steady state with the cycle operating with a pre-established load level and demand After 300 seconds have elapsed, a sudden variation in demand is produced due to shutdown or startup of one of the industrial consumers. Since increase in demand is a controlled process, the aim is to determine the maximum allowable rate of increase which will not produce a variation in pressure beyond the specified limits. On the other hand, since reduction in demand is not a controlled process, a sudden stepped decrease is assumed.

5 RESULTS AND CONCLUSIONS

The following graphs are an example of the results obtained in a combined cycle trip. This case is based on an initial situation with 66 t/h export at 100% load and one of the boilers at the technical minimum. When trip occurs, the order is given for the auxiliary boiler to increase the load. While the boiler is working to obtain the steam export flow that existed prior to the trip, lack of steam is compensated with that contained in the high pressure area of the heat recovery steam generator. To this effect the high pressure control valve (PCV_HPEX) opens after the trip, diverting the steam -which in normal conditions would go to the condenser- through the turbine bypass towards the process steam export header.

Figures 3 and 4 illustrate the evolution of the system flows and pressures. We can see a dual transient, the first corresponds to the trip after 300 seconds and the second to the change in auxiliary boiler control mode 700 seconds after steam input from the cycle is shut off.

In the combined cycle under study, it is concluded that for steam export levels below 66 t/h there is no need to keep any auxiliary boiler in operation. For greater export levels, one or both should be kept at the technical minimum.

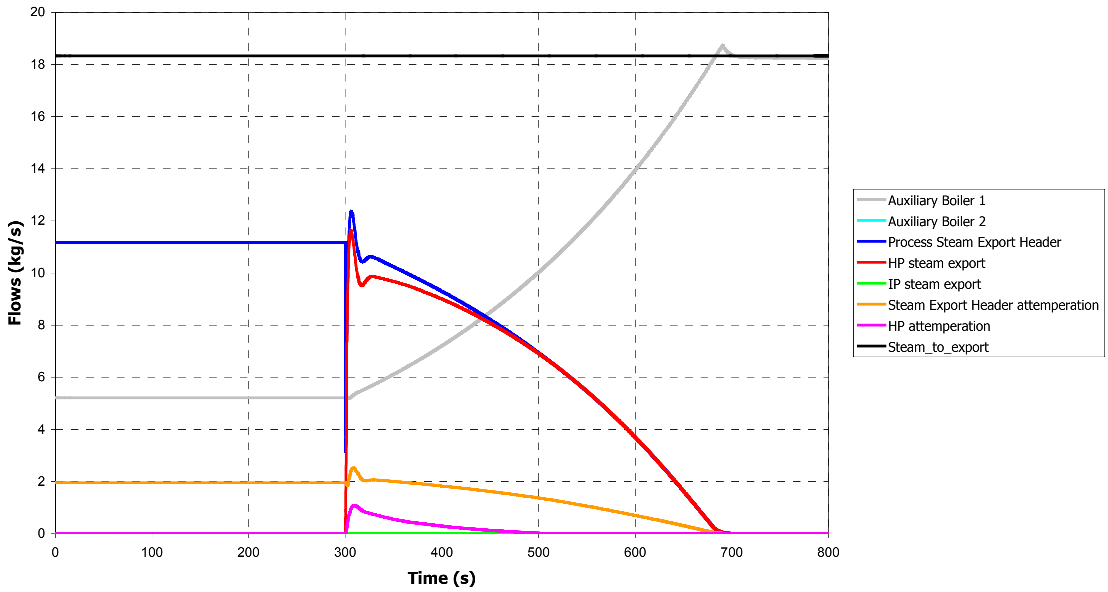


Figure 3

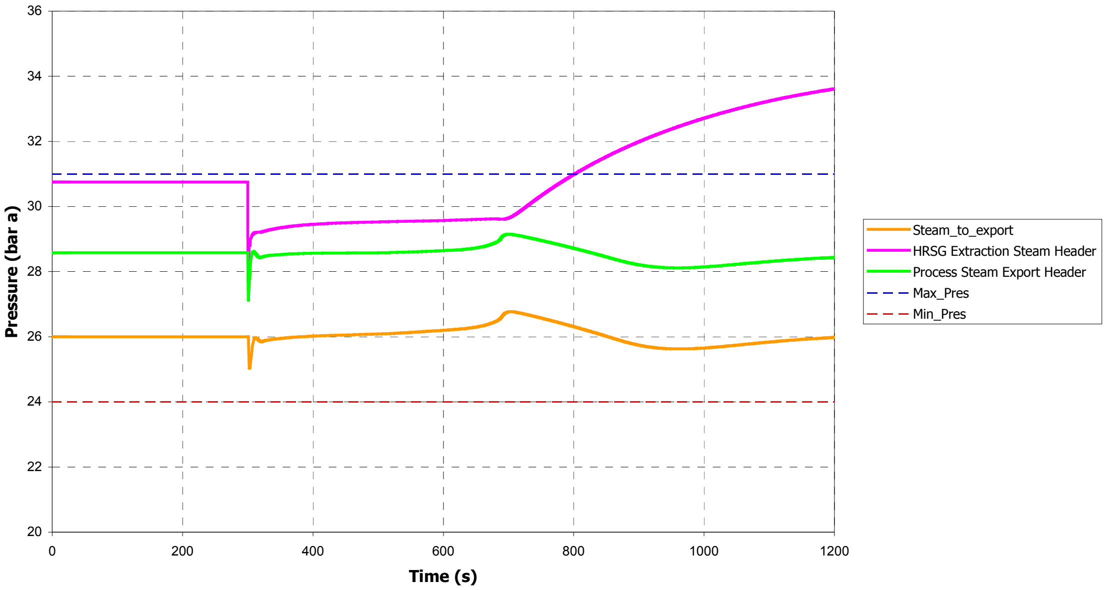


Figure 4

References

[1] Chapman, A., (1984) "Heat Transfer" 4th Edition

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