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Object-Oriented Simulation Approach to an Industrial Problem in a Combined Cycle Power Generation Plant

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Abstract

In this paper, Object-Oriented Modelling and Simulation (OOMS) is applied to a typical industrial problem, namely Primary Spinning Reserve scheduling in a Combined Cycle Power Plant. This allowed to optimise the control system so as to comply with the Network Code requirements in the presence of dynamic constraints posed by the plant main machineries. A simulation model of the plant was written in the Modelica language, making extensive use of the ThermoPower library, and thanks to the OOMS approach, said model was tailored to represent only physical parts strictly related to the problem. The availability of the simulator allowed to test different control solutions and to find the best one right from the system engineering phase. This has drastically reduced the commissioning time, helping also in the definition of the test schedule. Selected experimental results are presented and discussed, as both a validation of the model, and a proof for the efficacy of the adopted approach.

Keywords

Object-Oriented Modelling, Dynamic Simulation, Industrial Application, Experimental Results

1 CASE STUDY OVERVIEW AND PROBLEM STATEMENT

The presented study is related to a 420 MW Combined Cycle plant commissioned in Greece in the year 2010. The goal of the activity is twofold. The first requirement of the activity was to determine whether or not, and in the affirmative case to what extent, the plant with the control system specified by the vendor was capable of adhering to the network code as for the contribution to primary frequency regulation. The second task was to optimise the control strategy in such a way to enhance said compliance in the presence of some dynamic constraints posed by the available equipment, paying also attention to minimise the control energy cost.

To accomplish those tasks, a dynamic simulator of the plant (including the control system) was created, with the convenient level of detail, using the object-oriented Modelica language [6,7]. Extensive use was made of the first-principle models [1,2] of the ThermoPower library [3,5,8], aimed at the modelling of power generation processes and under continuous development at the Politecnico di Milano since several years. The simulation code was automatically obtained by employing the Dymola translator [4].

This paper describes the simulator, the simulation campaign performed, and the consequent answers to the activity questions. Finally, experimental results recorded during the plant commissioning phase are also presented.

2 NETWORK CODE REQUIREMENTS AND PROPOSED CONTROL POLICY

To achieve the Greek network code requirements, the plant

1. must be capable of contributing to the primary frequency regulation for up to a fixed percentage of its registered power, linearly decreasing to zero when the plant load percent load exceeds 97% (see Figure 1),
2. exerting the primary frequency contribution within 30 seconds from the frequency deviation event,
3. sustaining that contribution for at least 15 minutes,
4. and being capable of re-exerting the same primary contribution within 15 minutes from the frequency deviation event, assuming the network frequency set point was in the meantime recovered.

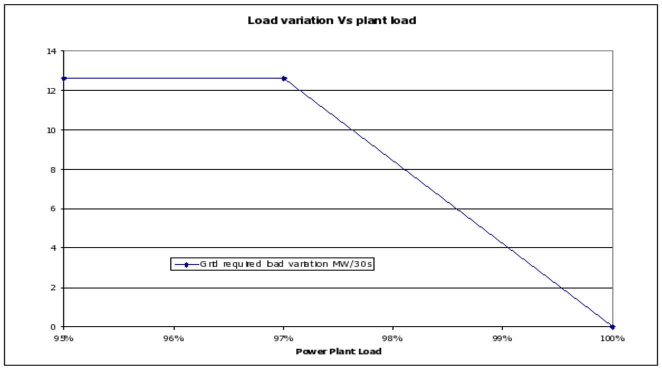

Figure 1: Primary reserve [MW] Vs plant load.

The main issue regarding the plant is the Gas Turbine (GT) power rate reduction at high loads; such a dynamic constraint in fact prevents the control system from managing primary regulation requests with the GT only. Moreover, owing to design choices inessential to the present discussion, the additional contribution provided by the post-firing in order to help the regulation under question is not sufficient either. Apparently, this is an exquisitely *dynamic* problem: the necessary power is available *at steady state*, but in general cannot be released within the prescribed 30 seconds.

As such, the envisaged solution is to over-pressurise the HP steam drum by an amount depending on the (additional) energy to be transiently drawn from the steam generator before the GT power (that increases at reduced speed near 100% load) becomes available. Then, after a frequency event and when enough GT power is available, the drum needs suitably over-pressurising again - and within convenient time limits - in order to be capable of re-exerting the primary effort.

3 MODEL ORGANISATION AND HYPOTHESES

The plant and control system model was written in the Object-Oriented Modelica language by using the Dymola simulation tool, and is composed of the following parts:

- Gas Turbine (GT),
- Heat Recovery Steam Generator (HRSG) and relevant Balance Of Plant (BOP),
- Flue gas path with Post-Firing (PF) combustor,
- Steam Turbine (ST) and relevant Condenser,
- Distribute Control System (DCS), including GT and ST governors.

The model was tailored to represent only the physical parts of the plant that are strictly related to the problem, and its level of complexity was adapted to achieve the tasks above. Particularly, the following simplifying assumptions were introduced:

- the water/steam path was represented using lumped-parameter models of the relevant parts; the parts that are not relevant for the problem under investigation (e.g. drain and vent systems) were suitably simplified, or replaced by convenient boundary conditions;
- the flue gas path, including the post-firing combustor, was represented using lumped-parameter models of the relevant parts;
- the GT and the condenser were represented by convenient tables, based on design data, as said components participate in the dynamics involved by the question to answer in this activity only by providing boundary conditions to the steam and flue gas subsystems;
- for the evaporative parts, no representation of the circulation loops in terms of individual components was introduced, and evaporator was described by compact model with three state variables, the circulation loop being thereby embedded in the three-state model;

- the electrical system and the plant connection with the geographic network were represented as proper frequency boundary conditions, limiting the scope to the behaviour of the generator frequency in the presence of a dominant frequency node (which for the presented analysis is a worst-case approach);
- as for the control system, only the main loops (levels, steam desuperheaters, feedwater preheater) were represented; the GT and ST governors were conversely detailed out, in order to reproduce the load variation dynamic as precisely as possible with the available information.

4 THE SIMULATION MODEL

The resulting simulation model is composed by subsystems, as depicted in Figure 2. It is possible to recognize the plant model (grey block), the control systems (white blocks), and the Human Machine Interface (HMI) sub-model (yellow block).

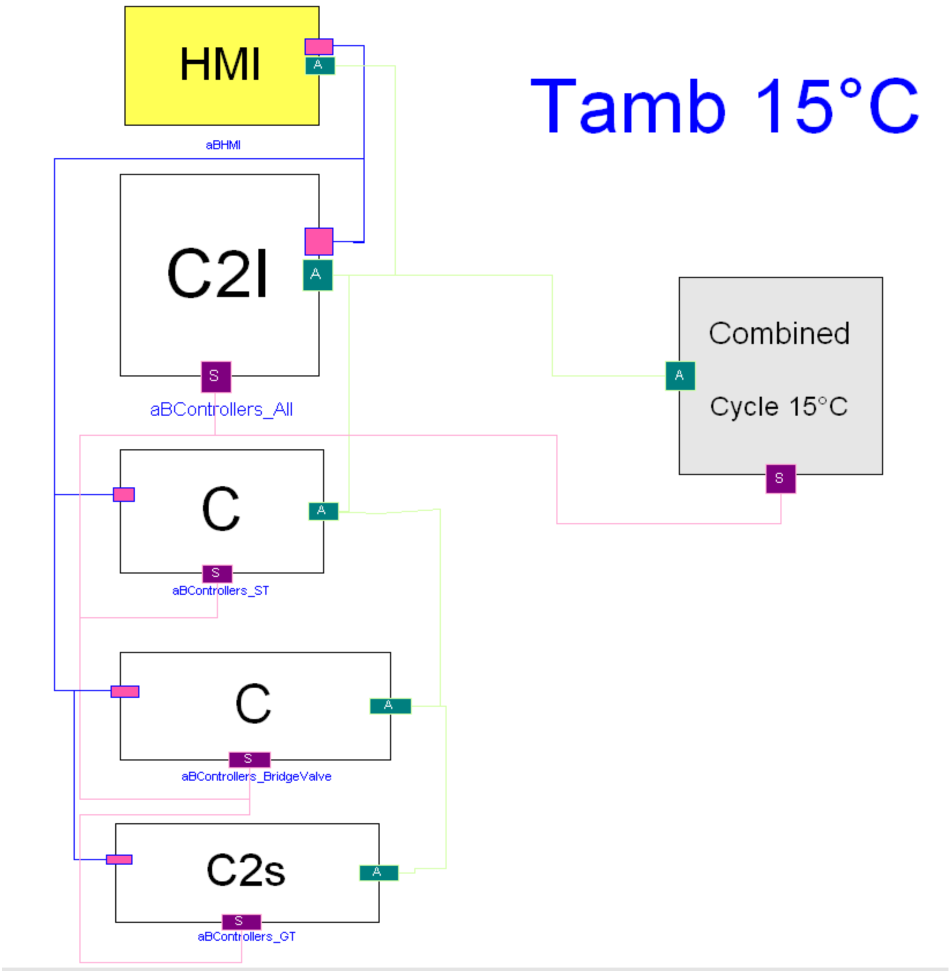

Figure 2: Modelica diagram of the entire simulation model.

The plant model is organised in physical nested sub-models, the first two nested levels depicted in the followings Figure 3 and Figure 4:

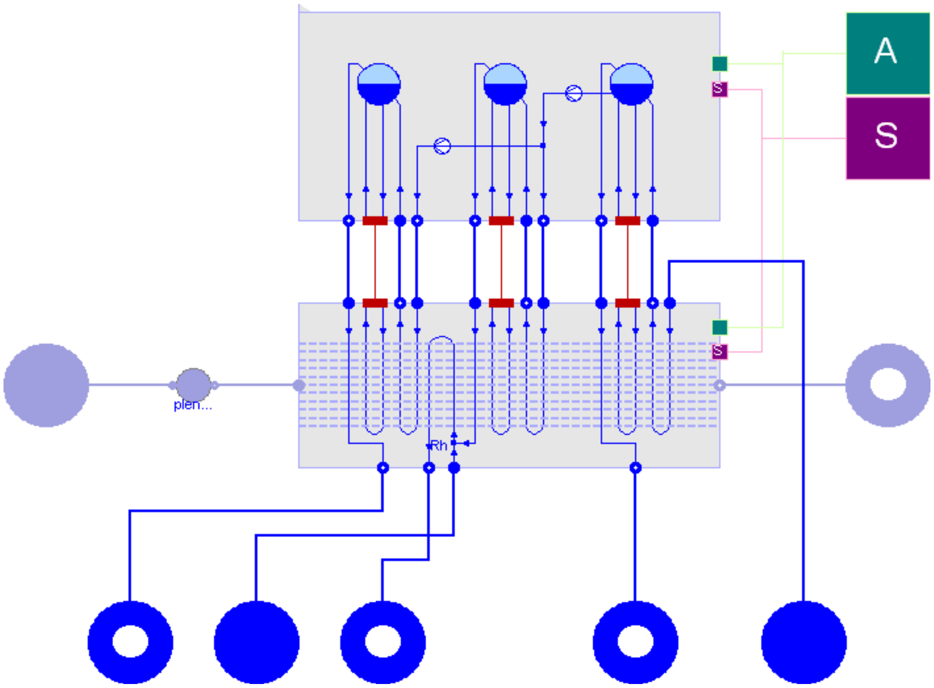

Figure 3: Modelica diagram of Water/Steam and Flue Gas paths.

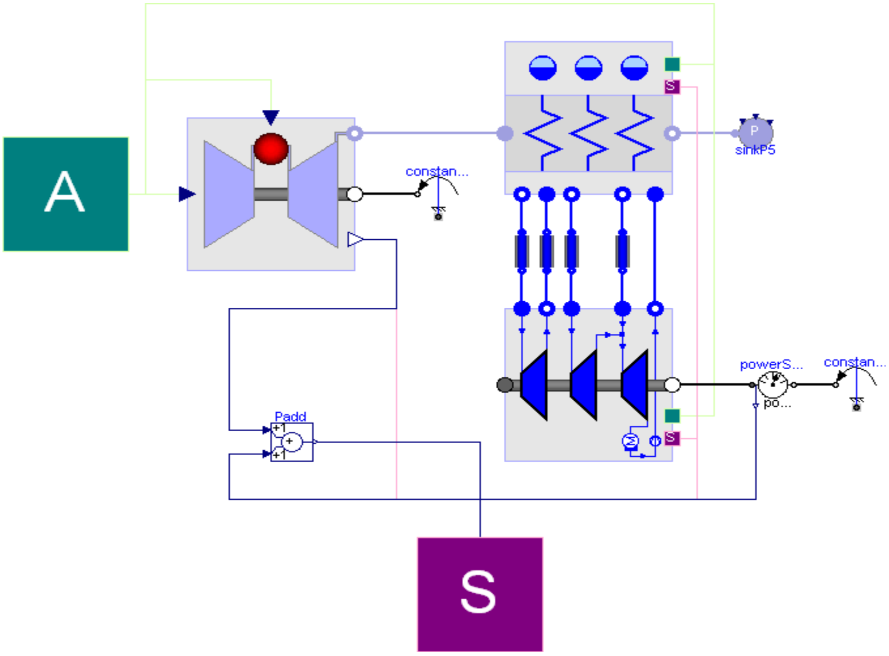

Figure 4: Modelica diagram of the overall plant model.

The control system model is described in a very similar way to the industrial DCS. To exemplify that, the following Figure 5 and Figure 6 show the GT and ST governors:

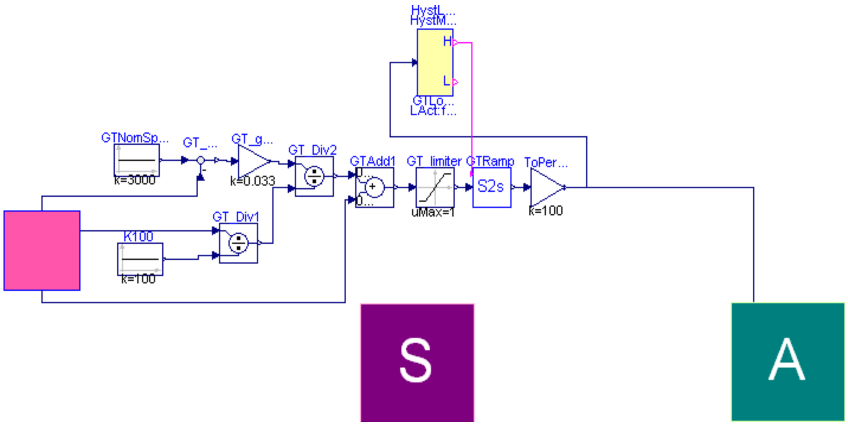

Figure 5: Modelica diagram of the GT governor.

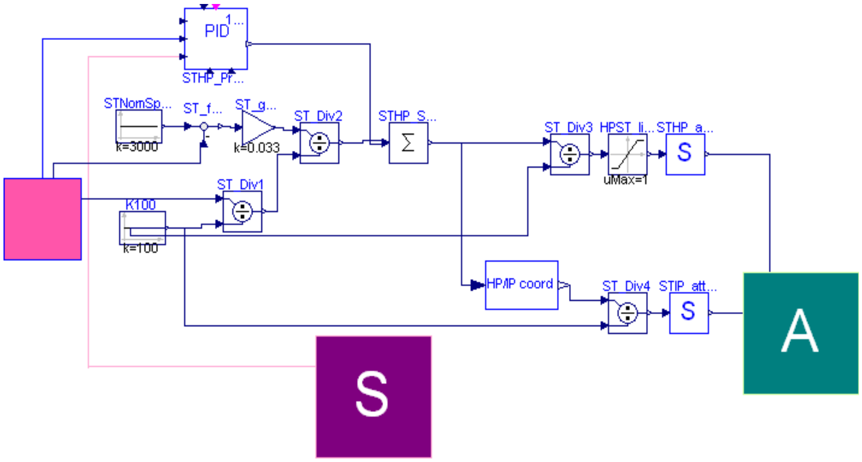

Figure 6: Modelica diagram of the ST governor.

Given that the study only required batch simulations, and for best reproducibility of the simulation runs, the HMI was emulated by a suitable collection of signal generators.

The most critical aspect of the control system policy addressed in this study was the ST governor, that is called to participate in the primary frequency regulation when the GT reduces its ramp rate. The first solution (termed STG1 in the following sections devoted to the simulation results) replicates the DCS vendor standard regulator. This solution foresees the post-firing at full load when the plant load is above 93%, which is the always the case in the present study. The ST pressure control is kept in regulation mode during the entire frequency transient. The high pressure steam set point is fixed to a pre-specified value (about 7 bar above the projected sliding value). Solution STG1 however exhibited some windup problems, that were solved (also introducing some control logic improvements) as described in the following solution (termed STG2 in the “simulations” section).

In the first place, when a primary request event occurs, the primary term (also termed the “$k\Delta f$” one, where k is the governor gain) must prevail in operating the ST arc valves over the drum pressure control, otherwise the drum over-pressurisation is immediately lost. Hence, initially one should set k to a very high value (corresponding to a very low droop) if possible, and in any case set the drum pressure controller into tracking mode, the tracking reference being the ST arc valve position as output by the $k\Delta f$ term. Then, when the GT power has reached the state in which it gives all the necessary primary power, the drum pressure control must conversely prevail, which is achieved by decreasing k if possible and in any case by removing the above tracking condition so as to overpressurise the drum again to the prescribed value. To determine when “the GT power has arrived” one can clearly check if the frequency set point is recovered or the total power produced by the plant is fulfilling the network code requirements, whatever happens first. The corresponding simulation model (STG2) implements the above rationale in a suitably simplified way. The reported simulations allow to state that the situation is correctly described by the statements of the previous paragraph, and the proposed control solution is adequate.

The second critical aspect of the control policy is related to the “bridge valve” that injects the steam from the intermediate pressure (IP) section of the HRSG into the ST high pressure (HP) steam exhaust reheater. Said valve is operated to maintain approx 1.5 bar drop between the IP drum steam outlet and the mixing point of that steam with the HP steam turbine exhaust, upstream the reheating section of the HRSG. The role of the bridge valve is to allow a correct management of the mixing between the HP turbine exhaust and the IP steam, particularly during the pressure transients caused by a frequency event requiring the plant to exert its primary regulation action. More precisely, during a frequency transient the bridge valve will be open (a quick opening to 100% will be produced by the control 2 seconds after the frequency deviation event) in order to compensate for the pressure increase at the HP steam turbine discharge, therefore avoiding the IP steam flowrate reduction. Such a policy also reduces the probability of overpressure phenomena in the IP drum (and thus the risk of vent/PSV opening) by preventing the closure of the IP steam check valve at the reheater inlet.

5 SIMULATION ACTIVITY AND RESULTS

Prior to the simulations, the model was aligned to the available data. In doing so, the most critical issue is the determination of the heat exchange coefficients that were aligned to the steady state computations provided by the HRSG vendor. Said thermal coefficients alignment has however revealed a significant dependence on the plant operating conditions. Given that, in order to maintain an acceptable model complexity for the sake of simulation performance, a different model and initial state parametrization was determined for each of the cases to replicate. The justification for said modus operandi is that in each of the resulting manoeuvres the plant does not move away from the initial steady state so much to invalidate the so obtained (local) model. The estimated error in the resulting transients is small enough with respect to the correspondingly estimated operating margin to allow trusting the obtained simulations for the purpose of this study.

As for the boundary conditions representing the network, in the absence of any load rate information, a worst-case attitude was taken: the event giving rise to a primary regulation request is represented as a frequency step of a value that saturates the primary regulation set point of the GT (i.e., |Δf| > 200mHz), without return to the set point value, which appears a conservative requirement for this study.

The set of simulations is organised in two subsets depending, on the used ST governor (i.e., STG1 or STG2, as explained above) .

6 SIMULATION SET STG1

These simulations utilise the STG1 governor, the PF is fixed to 100% and the HP pressure set point is 7 bar over the design sliding pressure. The pressure across the bridge valve is kept to 1.5 bar. Simulation runs were executed in the followings load conditions: GT at 93% load (i.e. GT operation close to the ramp rate reduction range), GT at 95% Load, GT at 97% load, GT at 98% load (i.e. GT Cold base load) and GT at 99% load (i.e. GT close to the output temperature control (OTC) operation). The following Figure 7 and Figure 8 show, in different time intervals, the simulation results at environmental temperature of +15°C:

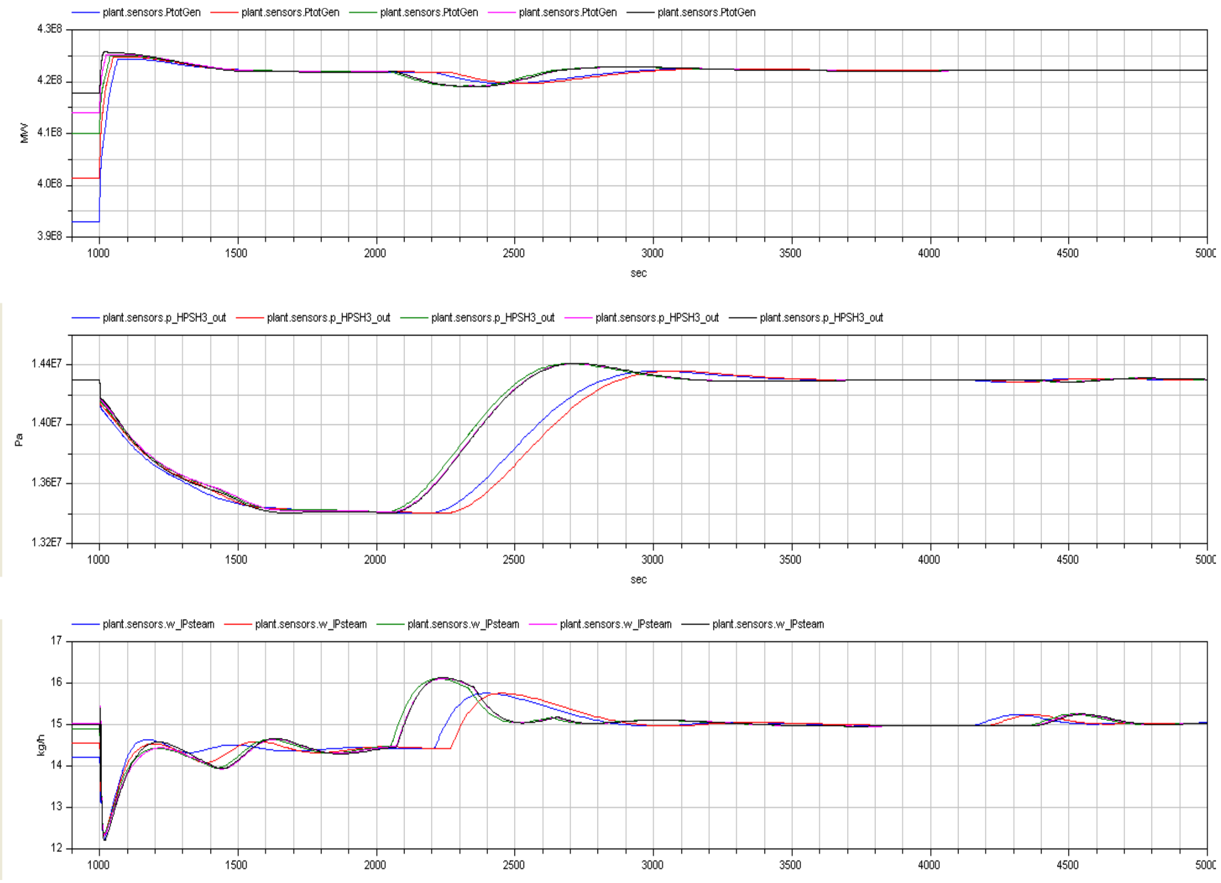

Figure 7: Top: Total generated power [W]; Middle: Stem pressure at HRSG HP outlet [Pa]; Bottom: IP drum steam flowrate [kg/s] in case STG1.

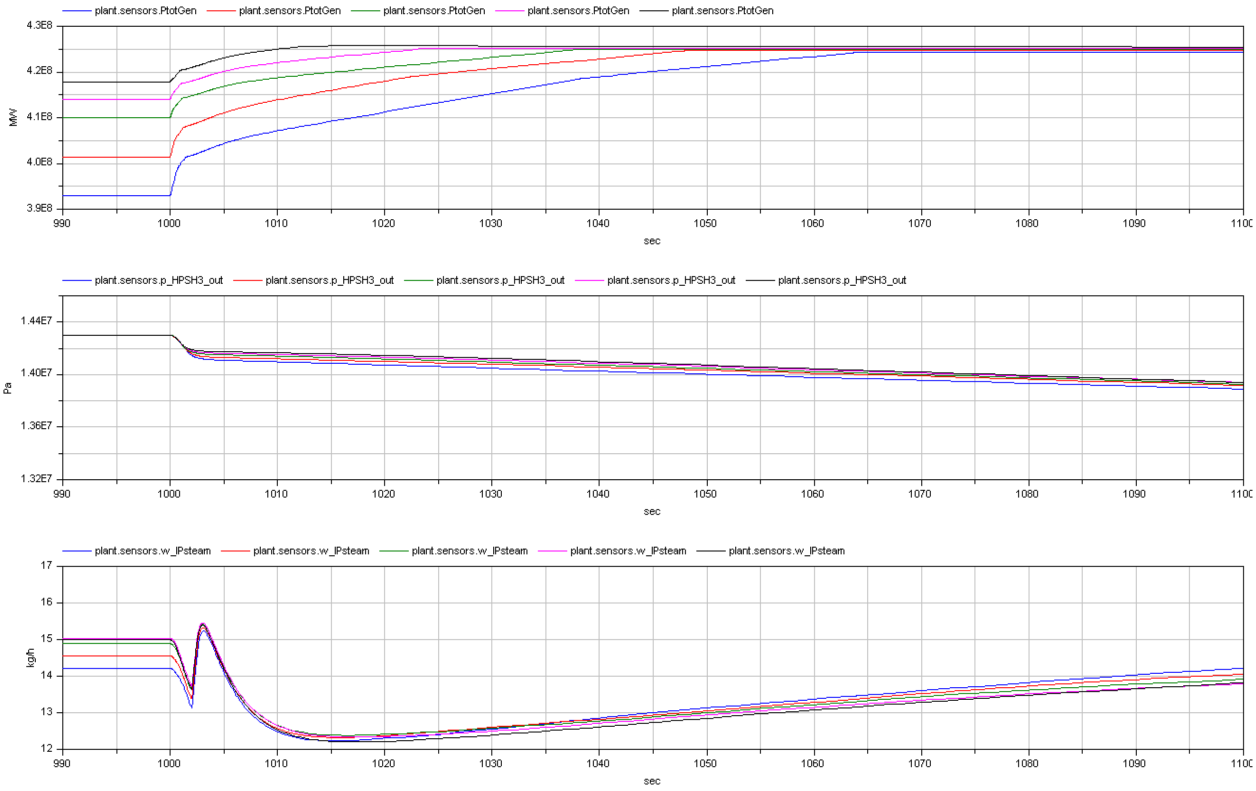

Figure 8: Top: Total generated power [W]; Middle: Stem pressure at HRSG HP outlet [Pa]; Bottom: IP drum steam flowrate [kg/s] in case STG1.

Referring to the figures above, the following results were obtained from the simulations run: the active power increment within 30 seconds was between 7,85 MW (worst case) and 22.33 MW (best case). At the reference case (GT at 97% load) the active power increment within 30 seconds was 13,25 MW (12,08 MW at steady state). The HRSG re-pressurisation average time was about 10÷12 minutes.

Starting from those results, one can observe that the power objective 30 seconds after the event is met. The problem is that the ST governor exhibits an apparent wind-up phenomenon. Owing to that, the HP drum pressure drops to excessively low a value, in turn causing two undesired effects. First of all, the re-pressurisation time becomes too large. Also, during the re-pressurisation, the relative controller behaviour causes a temporary reduction of the total power produced, i.e., a transient violation (by approximately 1.5 MW in average) of the network code prescriptions. Also, small variations of the IP steam flowrate are observed. Their entity does not affect the plant operation, however.

7 SIMULATION SET STG2

These simulations utilise the STG2 governor, the *rationale* and operation of which were summarised above, and aim at showing the improvements that this solution yields with respect to the standard one modelled by STG1. In the STG2 simulation runs, the

HP pressure set point is modulated based on the HP steam flowrate, as illustrated in Figure 9, left plot; also the PF is modulated, based on the GT load, as shown in Figure 9, right plot. The pressure across the bridge valve is kept to 1.5 bar.

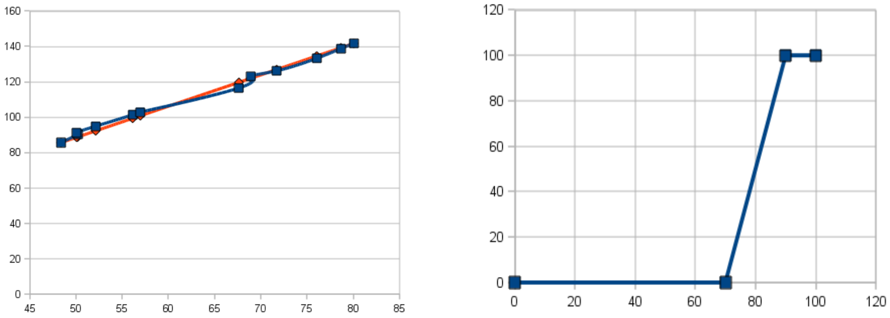

Figure 9: HP steam pressure set point [Pa] as a function of HP steam flow [kg/s] (left) and PF set point [%] as a function of GT load [%] (right) in case STG2.

Simulation runs were executed at same load conditions as in the previous simulation set.

The following Figure 10 and Figure 11 show, in different time intervals, the simulation results at environmental temperature of +15°C:

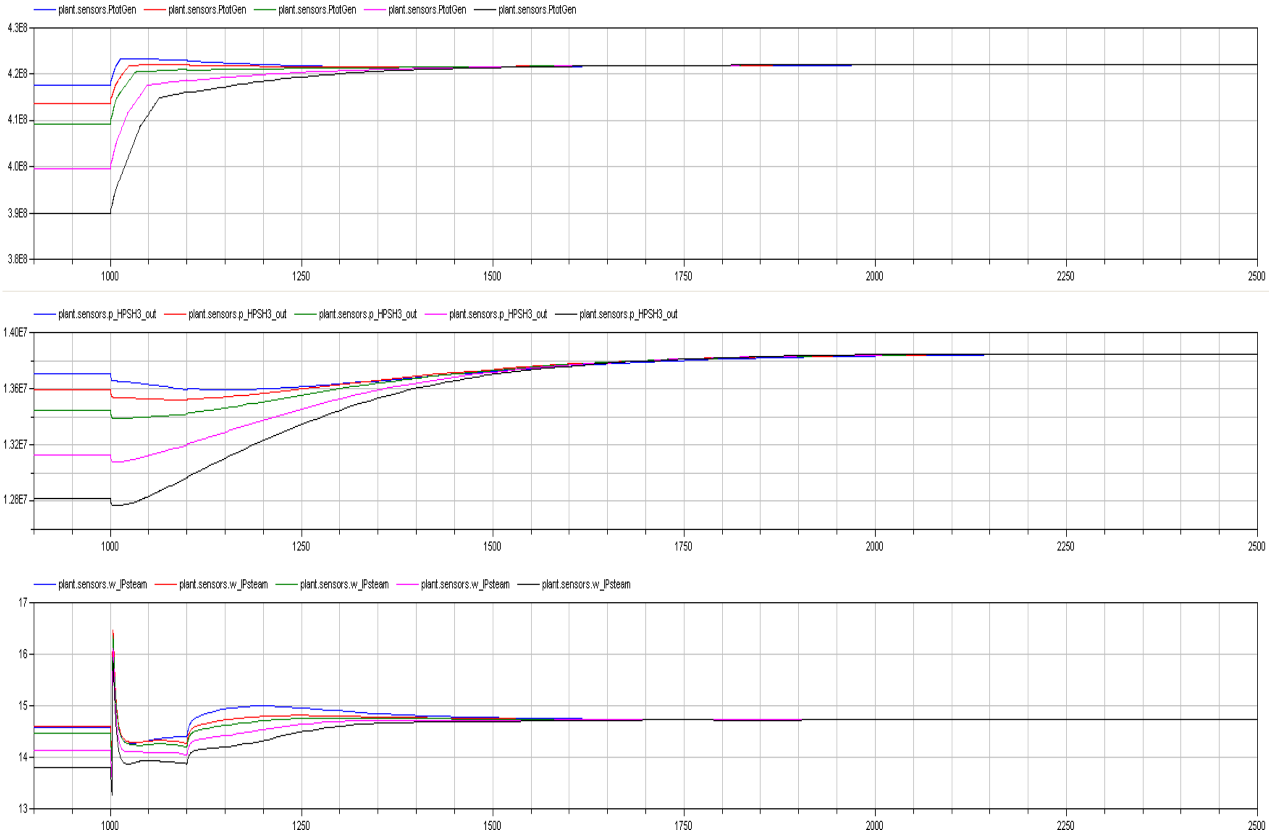

Figure 10: Top: Total generated power [W]; Middle: Stem pressure at HRSG HP outlet [Pa]; Bottom: IP drum steam flowrate [kg/s] in case STG2.

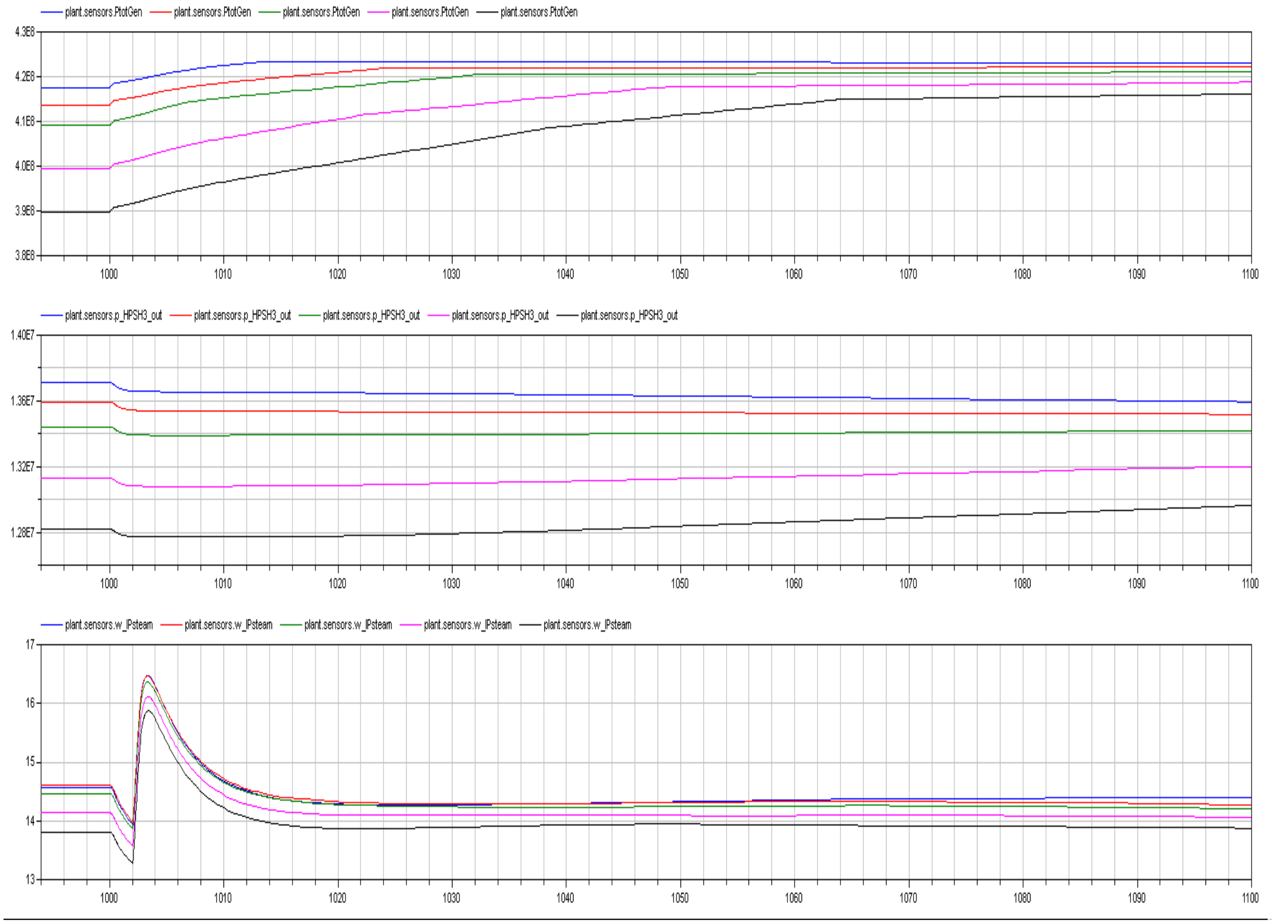

Figure 11: Top: Total generated power [W]; Middle: Stem pressure at HRSG HP outlet [Pa]; Bottom: IP drum steam flowrate [kg/s] in case STG2.

With reference to figures above, the following results were obtained from the simulations run: the active power increment within 30 seconds was between 5,7 MW (worst case) and 15,16 MW (best case). At the reference case (GT at 97% load) the active power increment within 30 seconds was 12,95 MW (12,71 MW at steady state). The HRSG re-pressurisation average time was about 10 minutes.

Starting from these results, the following remarks can be made: the primary power target, both 30 seconds after the frequency event and at steady state, is met; the ST governor STG2 significantly reduces the HP and IP drums depressurisation, therefore leading to a faster re-pressurisation (far within the network code requirements); finally, here too there are some very small IP steam flowrate fluctuations.

8 EXPERIMENTAL RESULTS

An important characteristic of the presented study is that the obtained simulation results were actually checked in the field, as exemplified by the few samples reported in this section.

The following Figure 12 and Figure 13 show the DCS trends recorded during the power tests executed in the commissioning phase of September 2010. The STG2 control policy was implemented in the ST governor and the test was executed with the following plant asset: GT at 97% load, PF fired and modulated according to the curve in Figure 9, right plot; HP pressure set point 8 bar over the natural sliding pressure, pressure across the bridge valve kept at 2 bar. The frequency error injected to the ST and GT governor was -200mHz (corresponding, at GT 97% load, to a maximum primary frequency contribution of 12.65 MW to be released to the network within 30 seconds). The environmental temperature was about 23°C.

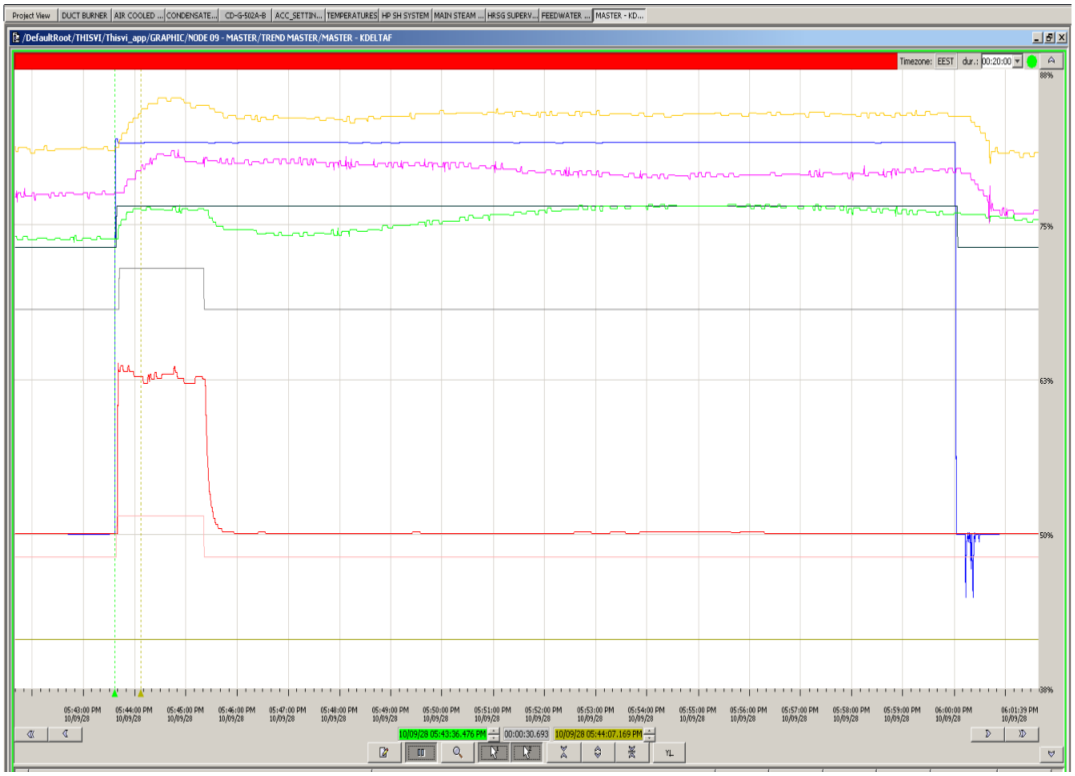

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Figure 12: Power transient;
Red/Blue: ST/GT Primary frequency action request
Magenta: GT active power [span -60, 330 MW],
Green: ST active power [span -60, 195 MW]
Yellow:Active Power exported to the network [span 0, 450 MW]

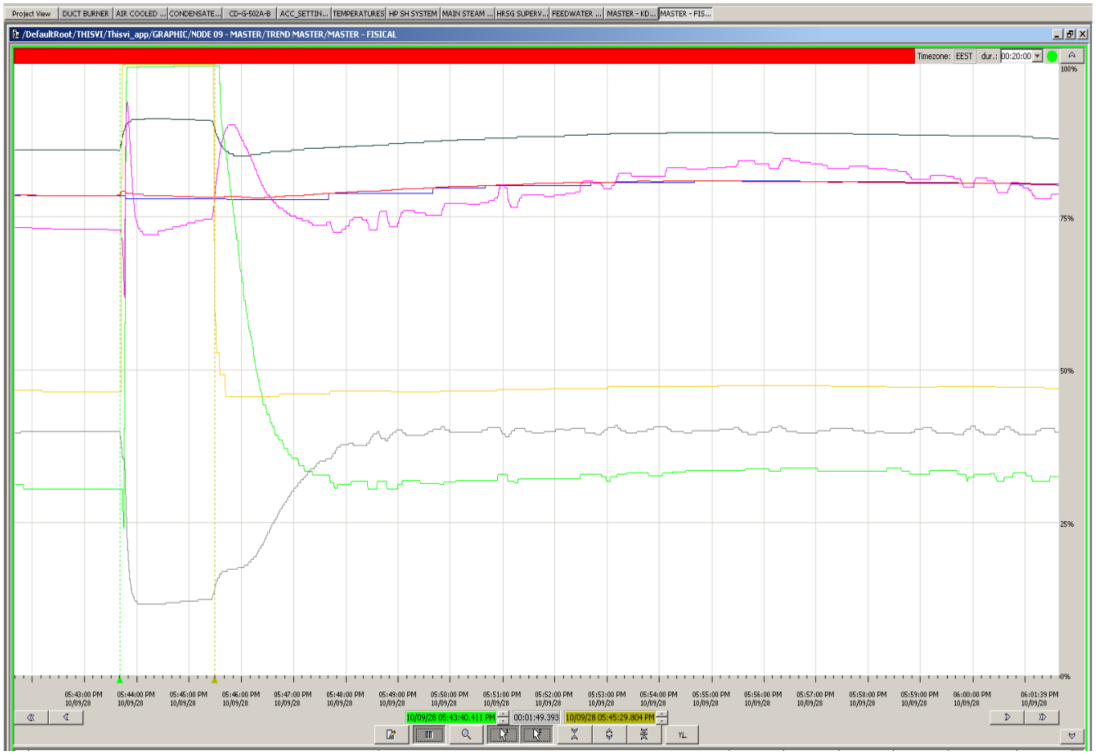

Figure 13: Pressure transient
Red/Blue: HP steam set point and actual value [span 0, 160 bar]
Grey: delta press. across bridge valve [span 0, 5 bar];
Yellow:ST HP control valve position [span 0, 100%]
Green: bridge valve position [span 0, 100%];
Magenta: IP drum steam flowrate [span 0, 67 t/h]

The following results were thus *actually* achieved: the active power increment within 30 seconds was of 6,8 MW for the GT and of 6,17 MW for the ST, for a total of 12,97 MW exported to the network. The average of about 12÷13 MW was maintained for 15 minutes, i.e., along the entire frequency transient. The HRSG pressurisation was restored within 11 minutes. The plant had therefore fulfilled the Greek network code requirements. Comparing the experimental results with those of the simulations, it is possible to say that the latter have reproduced in detail the actual plant behaviour, in terms of both power increment and pressure dynamic. In other words, we can say that the experimental results have validated the simulation. Moreover, it is possible to see that the tests on the plant showed a little downgrade in the GT performance with respect to the simulation, probably due to the intervention of the OTC control (not represented in the GT model). This power gap has been compensated by the ST performance, slightly higher than the simulated one (which may be explained taking into account the radiative contribution of the PF, that was not considered in the heat balance supplied by HRSG vendor, and consequently not represented in the simulation model).

9 CONCLUSIONS

An application of OOMS to an industrial problem was presented, by means of the Modelica language. The problem had some specific features: first, it is fundamentally "dynamic", therefore not solvable by means of the "steady state" tools normally used during the engineering phase; second, it mainly concerns a question of "control policy", as the sizing of the main machinery was already fixed at the time of the study. This method allowed to test different solutions and to find the best control policy starting from the engineering phase, allowing also to test the DCS implementation before the commissioning. Moreover, the obtained results allowed to minimise the number of tests on the real plant, optimising the commissioning scheduling and reducing the total amount of energy injected to the network during the test phase, as often required by the cost constraints applied to the power production during the commissioning. Finally, from the simulation point of view, the adopted modelling paradigm (open models, first principle equations) allowed to tailor the model to the part of the plant actually relevant for the problem, minimising the complexity of the final simulation code (therefore minimising the simulation time and the computing effort) and the number of the parameters to be tuned, thus confirming the efficacy of the OOMS paradigm beyond previous applications of it, as shown e.g. in [9].

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