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An optimization procedure of the start-up of Combined Cycle Power Plants

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Abstract: This paper presents an optimization procedure for the definition of the gas turbine load profile during the hot start-up of Combined Cycle Power Plants (CCPP). First a dynamic model of CCPP is briefly described, together with its implementation in the Modelica language. Then, an identification procedure is developed to determine a simplified model to be implemented in Matlab/Simulink and to be used for the solution of the optimization problem. This simplified model is built by interpolating a number of linear estimated models with local validity. The load profile is assumed to be described by a suitable function, whose parameters are optimized by solving a minimum time problem subject to the plant (simulator) dynamics and to a number of constraints to be imposed on the main plant variables, such as temperatures, pressures, thermal and mechanical stresses. A number of simulation experiments is reported to witness the performance of the proposed approach.

Keywords: Combined cycle power plants, start-up procedures, control, optimization, simulation, model identification.

1. INTRODUCTION

Combined Cycle Power Plants (CCPP) are nowadays widely diffused for their improved efficiency levels and reduced pollutant emissions with respect to traditional oil or coal fired plants, see (Watson, 1996). However, they are often managed at full load because of significant losses of efficiency at partial load, even though the increasing energy demand and grid regulation difficulties due to the energy market liberalization would require a more flexible management. For these reasons, it is of interest to develop new and efficient management strategies, either for control at partial or full load (Aurora et al., 2005), or for the start-up and shut-down phases. This second topic is of paramount importance since, as it is well known, the lifetime of CCPP is mainly related to the thermal and mechanical stresses reached during the start-up. For this reason, both in academia and in industry, many efforts have been devoted to determine procedures reducing the start-up time while keeping the life-time consumption of the most critically stressed components under control, see e.g. (Franke et al, 2003, Krüger et al., 2001, 2004, Bausa and Tsatsaronis, 2001a, 2001b, Smith et al. 1996, Xu et al. 2000, Ferrari-Trecate et al., 2002, Casella and Pretolani, 2006, Albanesi et al. 2006, Faille and Davelaar, 2009).

In this paper, a novel model-based approach to the optimization of the Gas Turbine (GT) load profile to be used in the start-up phase is presented. Specifically, first a physical model of the plant is developed together with a simulation environment in the Modelica language (Section 2). This simulator is then considered as the "reference plant" to be used to produce the input-output data required for the development of a simplified model based on interpolated locally identified linear models (Section 3). In turn, the interpolated model is used to compute the optimal load profile during the start-up by assuming that it can be described by a parametrised function, whose parameters are computed by solving a minimum-time optimal control problem subject to the constraints imposed by the plant dynamics and by the maximum peak value of the stress (Section 4). Finally, the optimal load profile is applied to simulate a start-up procedure on the original detailed Modelica simulator, so validating the overall project (see Section 5). Some final remarks and hints for future developments close the paper (Section 6).

2. PLANT MODEL AND MODELICA SIMULATOR

Many dynamic models of CCPP have been proposed in the literature and used for control design and for the optimization of the start-up procedure, see e.g. Aurora, 2004, Aurora et al. 2005 and Casella and Pretolani, 2006. In particular, a detailed description of the elementary models based on first principle equations (mass, energy and momentum balances) of the main elements of a CCPP are reported in Aurora (2004), where the interested reader is referred to. Models of the thermal and mechanical stresses have been developed in Leporati et al. (1993), Lausterer (1997). In Casella and Pretolani (2006), a detailed simulation model was developed for a plant composed by a gas turbine unit (GT), coupled to a heat recovery steam generator (HRSG) with three levels of pressure, driving a steam turbine (ST) group. The simulator was based on the Modelica ThermoPower library, see Casella and Leva (2003, 2006), and was parametrised with design and operating data from a typical unit. The simulator was then validated by replicating a real start-up transient, as recorded by the plant DCS.

In this work, the simulator described in Casella and Pretolani (2006) has been adapted to a plant with one level of pressure. This makes it possible to obtain a more tractable dynamic model for identification and optimization purposes while keeping the main characteristics of the problem.

The main components of the simulated plant are:

Gas Turbine: the gas turbine (GT) generates electric power and hot flue gas. It includes local control and its controlled input is then its load reference (*GTload*) expressed as a percentage of its maximal power. Its characteristics are: maximal power 235 [MW], nominal flue gas flow rate 585.6 [kg/s] and nominal fuel flow rate 12.1 [kg/s].

Heat Recovery Steam Generator: the heat recovery steam generator (HRSG) generates steam from the heat of the flue gas of the gas turbine. Its main components are the economizer, the steam drum, the evaporator and the superheater. Its controlled inputs are the drum feedwater flow rate and the desuperheater water flow rate, this later enabling to control the temperature of the steam after the superheater. Its characteristics are: nominal steam flow rate 70.6 [kg/s] and nominal steam pressure 129.6 [bar].

Steam Turbine: the steam turbine (ST) is a single stage turbine that generates electric power from the steam. It has three controlled inputs: the position of the bypass valve, the position of the admission valve and the generator grid breaker that connects the turbine to the grid. Its nominal power is 85 [MW].

Condenser: The condenser of the steam that comes from the ST through the bypass valve or the turbine is modeled, in a simplified way, as a sink with constant pressure (0.1 [bar]).

The variables that are considered of interest by engineers for the start-up have been defined as outputs of the model and are:

- power of gas turbine;
- fuel flow in gas turbine;
- drum level of the HRSG;
- temperature of steam in superheater (*TSH*);
- steam pressure;
- superheater header stress;
- temperature of steam in the steam line;
- power of steam turbine;
- frequency of steam turbine;
- rotor stress of steam turbine;
- steam flow.

This model is designed to study the hot start-up procedure of the plant. The *GTload* is then assumed to vary from technical minimal conditions (7.5% of the full load) to full load conditions, i.e. from 17.625[MW] to 235[MW]. Local controllers have been designed to ensure adequate working conditions for the plant:

- a PI loop that controls the drum feedwater flow in order to regulate the drum level at a constant value,
- a loop that controls the position of the admission valve in order to maintain the pressure at a minimum value (60 bar for instance) that is active when the load is below 50%.

Finally in this study, only the last stage of the start-up, the load increase, is considered. It is then assumed that,

- the by-pass valve is closed;
- the steam turbine is connected to the grid;
- the desuperheater feedwater flow gets a value close to its nominal value (0) and the admission valve is at minimum opening when the pressure control loop is not active;
- the load of the gas turbine is set to 15%.

Therefore, the *GTload* signal is the input that has the biggest range and induces most of the dynamics characteristics during the last stage of the start-up.

3. IDENTIFICATION OF INTERPOLATED LOCAL LINEAR MODELS

Modelica, together with the ThermoPower library (Casella and Leva 2003, 2006), is an extremely powerful tool for the rapid development of accurate physical models of thermo power systems, and in particular of CCPP. On the other hand, this model is designed for simulation and uses extensively Modelica features such as genericity and inheritance that make it unsuitable for optimization. For this reason, it has been decided to develop a simpler identified model capable to represent the main dynamics of all the CCPP output variables of interest. According to the approach proposed in Foss and Johansen (1993), Johansen and Foss (1995), the overall model is composed by a number of local linear identified models combined by means of a scheduling variable, the *GTload* in our case, which describes their local validity through suitably defined membership functions. The approach considered is based on the following main steps:

- a number N (N=10) of significant values of the *GTload* is selected as operating points, namely 7.5%, 15%, 25%, 40%, 50%, 57%, 60%, 65%, 75%, 100% of the full load; this set of values is selected to cover the full range of the variable and is more dense around 60% where the plant exhibits a strongly nonlinear behaviour;
- the Modelica simulator is used to determine the steady state conditions at any point;
- small step variations are imposed at each operating point to the load, to the desuperheater flow and to the admission valve (when it is free);
- the induced transients of the output variables of interest are collected and subsequently used for the identification of the transfer functions $G_i(z)$ of linear models with local validity. The identification procedure is performed with the Matlab Identification toolbox. More specifically, ARX (AutoRegressive eXogenous) and OE (Output Error) models are used. For all the variables, first or second order models are sufficient to describe the transients of the outputs with satisfactory results. An example of the results achieved is shown in Figures 1 and 2, which show the step responses of the

temperature *TSH* and of the header stress due to a small positive variation of the GT load at the 75% of its value and computed both with the Modelica model and with the identified one;

- *N* membership functions are defined and tuned, according to a trial-and-error procedure, each one providing the "degree of truth" $\mu_i \in [0,1], i = 1,...,N$ of the *i-th* local model based on the current value of the *GTload*. The ten membership functions selected in this work are depicted in Figure 3.
- *N* models Γ_i , *i=1,…,N*, used for interpolation are built, as shown in Figure 4, for any output variable. In the figure, *u* is the input vector, y_i is the output of the model, $(\bar{u}_i, \bar{y}_i)$ is the input-output equilibrium pair for the *i-th* working point specified by the corresponding value of the *GTload* and μ_i is the value of the associated membership function.
- The output *y* of the overall model is obtained as the sum of the outputs y_i, *i=1,…,N* of the local models Γ_i. Therefore, the complete interpolated model has the structure reported in Figure 5.

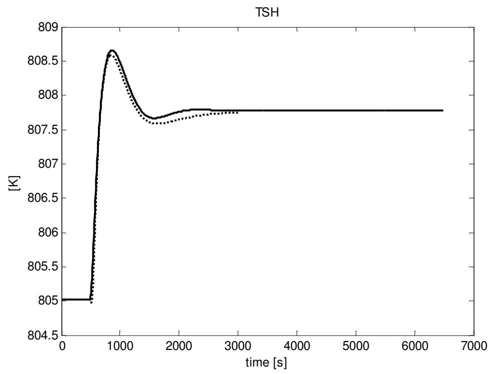

Figure 1: step responses of *TSH* with the Modelica (dotted line) and the identified models (solid line) at the 75% of *GTload*.

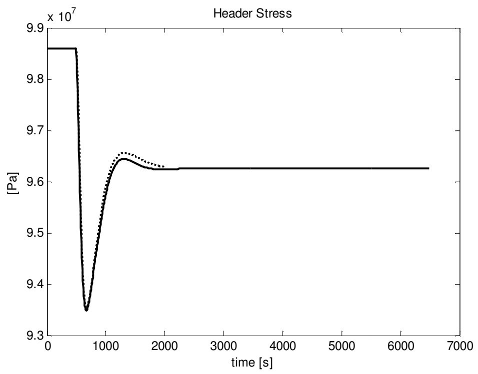

Figure 2: step responses of the header stress with the Modelica (dotted line) and the identified models (solid line) at the 75% of *GTload*.

The transients of the temperature *TSH* and of the header stress caused by a wide ramp variation of the *GTload* (from 100 to the 15% of the load) computed with the Modelica model (dotted line) and with the identified one (solid line) are reported in Figures 6 and 7. It is apparent that the identified model can reproduce the plant dynamics of interest with satisfactory accuracy, both for local and for large variations of the working point.

Concerning the adopted procedure to obtain the identified model, the number of operating points is important but it is remarkable that the most cumbersome and time consuming phase concerns the definition and tuning of the membership functions. To this regard, automatic procedures based, e.g., on the optimization of the quality of the open-loop simulation results over large transients could be devised to reduce the development time.

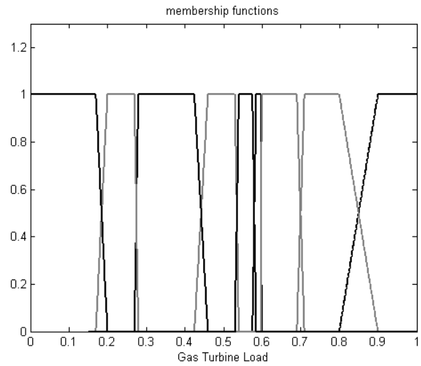

Figure 3: membership functions (x-axis: fraction of full *GTload*).

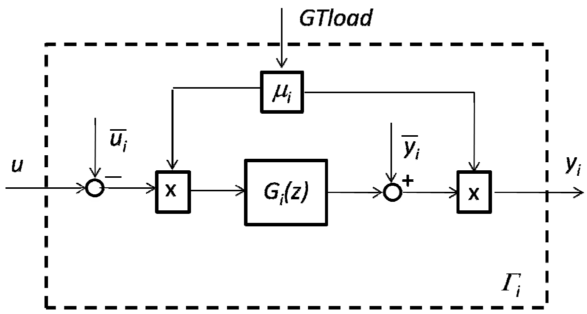

Figure 4: *i-th* local linear model with membership function.

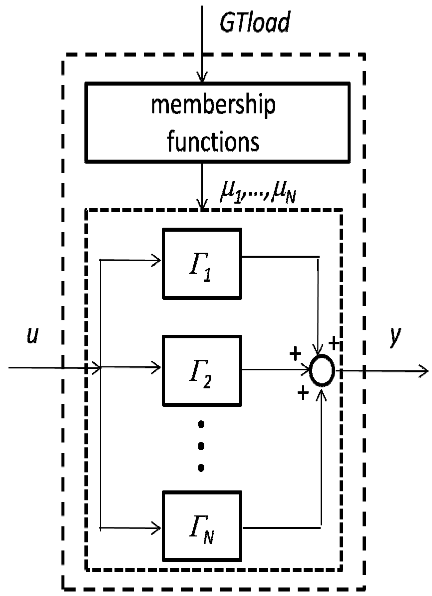

Figure 5: structure of the overall model for output y.

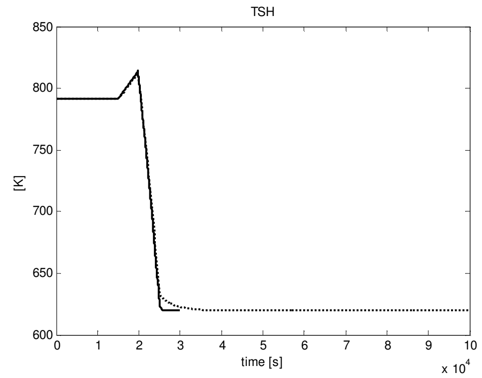

Figure 6: temperature *TSH* computed with the Modelica model (dotted line) and with the identified one (solid line).

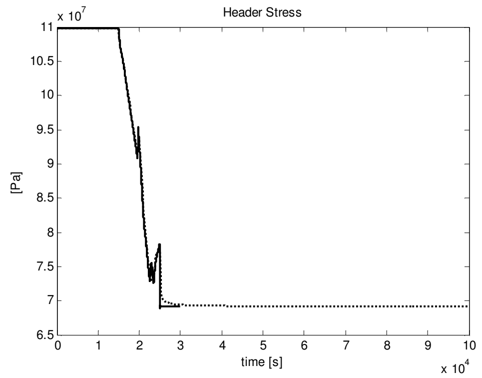

Figure 7: header stress computed with the Modelica model (dotted line) and with the identified one (solid line).

4. COMPUTATION OF THE OPTIMAL LOAD PROFILE

With the operating conditions described in Section 2, the main input that can be used to optimize the start-up is the load of the gas turbine. The problem is then to find the *GTload* profile that minimizes the time required to reach full load conditions while respecting constraints on the process variables; typically, it is required that temperatures, pressures and stresses remain into prescribed limits for safety and economical reasons.

More formally, the problem posed corresponds to a minimum time optimal control problem and can be stated as follows.

The CCPP model can be described by the dynamic system

$$\dot{x}(t) = f(x(t), d, L(t))$$

where x is the vector of state variables (temperatures, pressures, …), d is the set of (constant) external inputs (feed flow to the desuperheater, admission valve, by-pass) and L is the *GTload*.

Denote now by t_0 the initial time instant of the start-up procedure (conventionally it can be set t_0=0) and by t_f the final one. As for the load profile, it must be selected so that $L(t_0)=L_m$ and $L(t_f)=L_M$, L_m and L_M being the initial and final (full) load.

Assume now that the load is described by an increasing function $L(t,q)$ satisfying the boundary conditions above stated and where q is a vector of unknown parameters, which have to be selected through an optimization procedure.

Then, the problem of computing the optimal load profile consists of finding the value of the parameter vector q together with the final time t_f which solves the following optimization problem:

$$\min_{q,t_f} J = \int_{t_0}^{t_f} dt$$

subject to the constraints

$$\begin{aligned}
&\dot{x}(t) = f(x(t), d, L(t,q)) \\
&L(t_f, q) \geq L_M - \varepsilon_1 \\
&\left| f(x(t_f), d, L(t_f, q)) \right| \leq \varepsilon_2 \\
&g(x(t)) \leq 0,\ t_0 \leq t \leq t_f
\end{aligned}$$

where ε_1 and ε_2 are arbitrary small values (ideally equal to zero) and the corresponding constraints are included to guarantee that at time t_f the system is (almost) in stationary conditions and has reached (almost) full load. The last (vector) constraint includes, in general form, all the constraints to be imposed to the plant variables. Specifically, only constraints on the stresses during the start-up precedure have been included in this work..

Many functions *L(t,q)* can be chosen, such as sigmoid functions. In this work, the following *Hill function* has been chosen:

$$L(t,q) = L_m + (L_M - L_m)\frac{t^h}{t^h + k^h}$$

where $q = [h \quad k]$ is the parameter vector to be determined through the optimization procedure. Letting L_m=0, L_M=1, t_0=0, t_f=1, k=0.5, the Hill function for different values of h is shown in Figure 8.

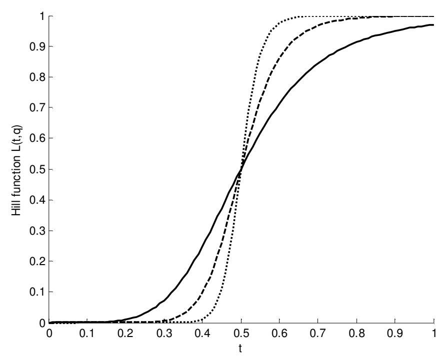

Figure 8: Hill function with *k*=0.5, L_m=0, L_M=1 and *h*=5 (solid line), *h*=10 (dashed line), , *h*=20 (dotted line).

As a simple simulation model is available, the optimization problem above can be solved numerically to compute the unknown parameters.

5. VALIDATION EXPERIMENTS

The optimization procedure described in the previous section has been implemented by imposing a number of constraints on the main plant variables. In particular, the header stress and the steam turbine stress have been imposed to not exceed 11e7 [Pa] and 2.25e8 [Pa], respectively.

The computed optimal load profile (Hill function) for a start-up phase (from 15% to 100%) is reported in Figure 9. Note that the start-up time is about 3.5 hours, but 90% of the response is obtained in 1 hour.

This optimal load profile has been computed with the identified interpolated local linear model and tested with the Modelica one. The transients of some relevant variables with this profile are reported in Figures 10 and 11. From these results it is apparent that the response of the two models are quite close to each other and that the computed optimal profile on the identified model allows one to reach with the Modelica models, the required full load conditions while respecting the imposed state constraints. In particular, the solution guarantees that the stress obtained during the transient does not exceed the design value.

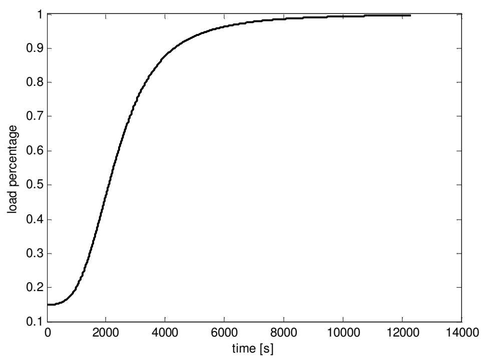

Figure 9: Optimal load profile.

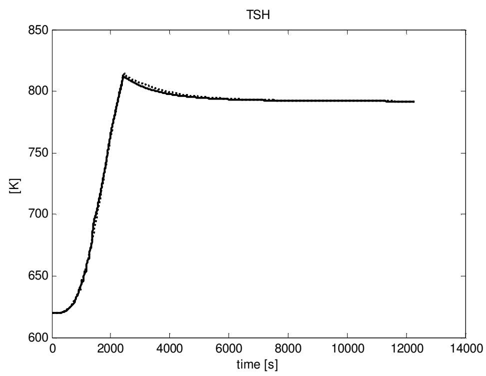

Figure 10: temperature *TSH* corresponding to the optimal profile of *GTload* computed with the Modelica model (dotted line) and with the Simulink one (solid line).

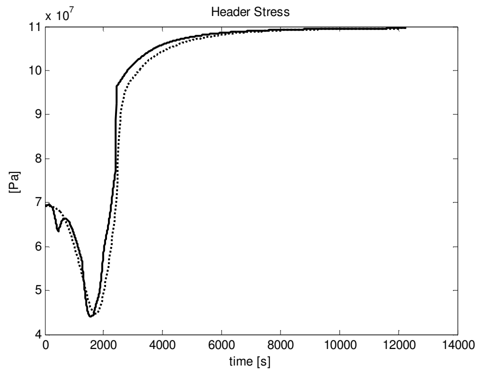

Figure 11: header stress corresponding to the optimal profile of *GTload* computed with the Modelica model (dotted line) and with the Simulink one (solid line).

6. CONCLUSIONS

The identified model that has been designed in this project has been used for an open loop optimization. The results of the optimization phase allow one to consider that it is accurate enough to be used as the prediction model of a MPC controller, so that potential deviations of the system from its expected value can be dealt with.

The project described in this paper can be developed in many different ways. The first open point is the relaxation of the operating conditions and the use also of the desuperheater flow and the admission valve position as optimization signals. This will require the specification of a systematic procedure to define the operating points where to perform local model identification and the subsequent optimization of the corresponding membership functions, as for a three dimension space the problem is more difficult to deal with.

Another point of interest is the selection of the function describing the input signals. In fact, the simple choice performed in this study may lead to very suboptimal solutions to the original problem. For example, concerning our results (see Figure 9), while Hill functions can guarantee fast and safe attainment of high load condition (90% of full load is attained in approximatively one hour), the final transient phase (90% - 100% of full load) could be made faster with a different choice of input function. In some cases, for example, the cascade connection of two Hill (or equivalent) functions could be useful to replicate the typical load profile used in the plants management.

Also, additional constraints can be included in the optimization problem formulation. For instance, the rate of change of the stress level might also significantly affect the plant longevity.

Finally, the problem considered here can be viewed as at the higher level of a hierarchical control structure where at the lower level suitable controllers for the main plant variables must be properly designed. It is necessary to study how the uncertainty on the lower levels can be taken into account with this approach at the higher level.

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