NONLINEAR MODEL PREDICTIVE CONTROL OF COMBINED CYCLE POWER PLANTS

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Abstract: The recent widespread diffusion of Combined Cycle Power Plants (CCPPs) is due to crucial technological advantages with respect to oil or coal fired plants. Among them, CCPPs guarantee higher efficiency and lower emissions. However, in the context of a deregulated energy market, better performances of the CCPPs control schemes are required during load transitions to allow for their use in grid frequency regulation.
In this paper, an innovative Nonlinear Model Predictive Control (NMPC) strategy is applied for the regulation of a detailed nonlinear model of CCPPs, specifically designed for control purposes and validated on real plant data. In particular, the steam temperatures of the Heat Recovery Steam Generator (HRSG) are controlled with NMPC and the plant efficiency is improved at partial load. The obtained results are compared to those achieved with a standard control scheme where the PID regulators have been accurately tuned to optimize the control performance.

Keywords: Nonlinear Model Predictive Control, Thermal Power Plants, Combined Cycle Power Plants

1. INTRODUCTION

Combined Cycle Power Plants (CCPPs) are composed by two main subsystems, the Gas Turbine System (GTS) fed by natural gas, see (Bathie, 1996), and the Heat Recovery Steam Generator (HRSG), where the heat of the gas turbine exhaust gasses is used to move a multistage steam turbine, see (Subrahmanyam *et al.*, 1995). Compared to traditional oil or coal fired plants, CCPPs guarantee both higher efficiency levels and reduced pollutant emissions, see (Watson, 1996). This second advantage is going to have a major importance in view of the constantly increasing strictness of the laws limiting the concentration of NOx and CO.

For the above reasons, CCPPs have encountered a great diffusion in the last decade, a large number of

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new plants has been built and many existing units have been repowered. However, it is well known that CCPPs have significant losses of efficiency at partial load, therefore they are usually fully loaded. This management policy forces the grid manager to use other kinds of power plants for the regulation of the power network. On the other hand, it is apparent that the growing diffusion of CCPPs, together with the increasing energy demand and grid regulation difficulties due to the energy market liberalization, will soon require the participation of Combined Cycles to the net frequency control (Kakimoto and Baba, 2003). Hence, the possibility to provide a better, more efficient and performance optimized regulation of Combined Cycles is of great interest. In fact, up to now only PID configurations have been used and the regulators tuning has been based on the selection of standard parameters and simple procedures, so that there is a significant opportunity to improve the control performances with a more sophisticated, model oriented approach.

In this paper the Model Predictive Control (MPC) technique is used to improve the control of the main steam temperatures inside the HRSG. In particular, the nonlinear MPC method proposed in (Magni and Scattolini, 2004) is applied to the detailed simulator developed in (Aurora, 2003). The adopted plant model is based on first principle laws describing the main heat transfer and fluid dynamics phenomena in an operating range corresponding to 70-100% of the nominal load, which is the standard operating range of a CCPP. The model has been tuned to reproduce the structure and the main features of a specific CCPP located in northern Italy.

The paper is organized as follows. In Section 2, the considered plant is briefly described together with the main assumptions introduced in the modelling phase. The conventional control scheme usually adopted for control of CCPPs is presented in Section 3. Section 4 is devoted to present the main features of the MPC algorithm as well as some details concerning its on-line implementation. Finally, in Section 5 different NMPC implementations for CCPPs regulation are discussed, and the main results of this study are presented and compared to those obtained with a standard control scheme where the PID regulators have been accurately tuned to optimize the control performance.

2. THE CCPP MODEL

The CCPP model, developed in the Matlab/Simulink environment, is composed by a number of elementary blocks representing the main plant components. The GTS includes the compressor, the combustion chamber and the gas turbine. The HRSG is formed by heat exchangers, drum boilers, mixers, attemperators, pumps, valves and steam turbine stages (see Figures 1 and 2). Conversely, the condenser and the alternators, also represented in Figure 2, have been neglected as well as some other elements of minor importance, like pipes and manifolds.

The main, general simplifying modelling assumptions are:

- the heat exchange phenomena have been described by temperature-based, rather than enthalpy-based, models, so avoiding the use of the Steam Tables (Int, 1996). A pressure-varying specific heat has been used to increase the validity range of the simplified heat exchangers models in the selected load range. The saturated steam and water properties have been implemented as properly identified polynomial functions of the pressure.

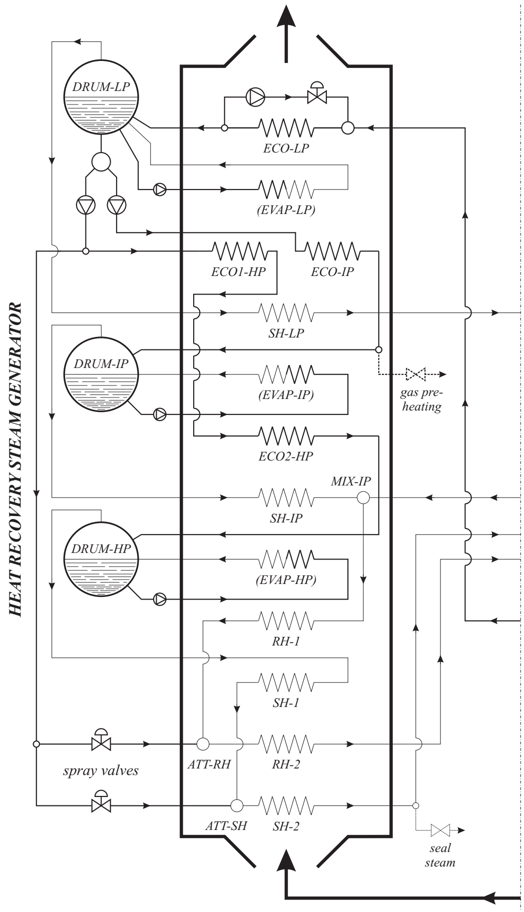

Fig. 1. Scheme of the reference CCPP: the HRSG.

- Fast dynamic phenomena have been neglected by adopting computationally efficient algebraic solutions. An algebraic momentum equation has been used to model pressure losses in the path between drum boilers and steam turbines. Fluid compressibility of the superheaters has been ignored, since it is negligible with respect to the drum boilers dynamics. In view of these assumptions, the steam fluid dynamic circuits have been modelled as systems of algebraic nonlinear equations, corresponding to the pressure levels of the HRSG. Their solution has been explicitly com-

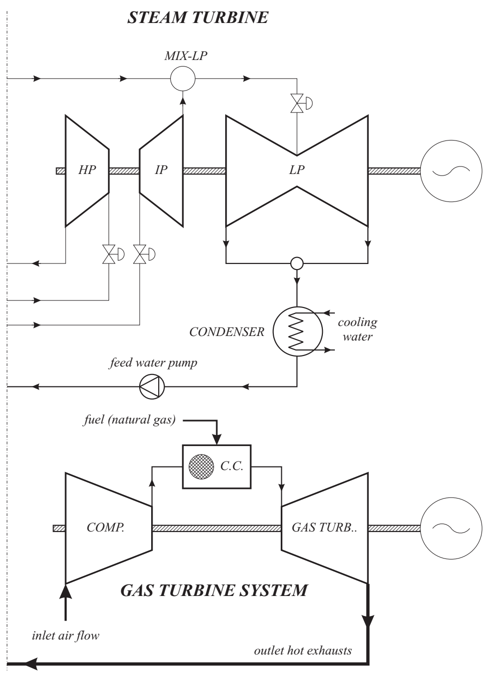

Fig. 2. Scheme of the reference CCPP: the Steam Turbine, the condenser and the Gas Turbine System.

puted off-line and implemented inside the simulator code.

- A similar approach has been followed to model the hydrodynamic system. In this case, the algebraic equations have been integrated by proper dynamic models describing the main actuators, valves and pumps.

The CCPP model has been tuned to reproduce a true installation located in northern Italy, the main characteristics of which are summarized in Table 1. Moreover, the model validation and the tuning of some parameters, such as the heat exchange coefficients, have been completed by comparison with an existing, highly detailed simulator of the same plant, developed in the ALTERLEGO modelling environment (Castiglioni *et al.*, 1993).

Table 1. Main features of the reference CCPP

Combined Cycle data	
net output	335 MW
net heat rate	1573 kcal/kWh
Gas Turbine data at normal load	
manufacturer	FIAT/AVIO
turbine inlet temperature	1367 °C
mean heat rate	2301 kcal/kWh
turbine exhausts temperature	564 °C
HRSG data at base load conditions	
HP steam pressure / temperature	128 bar / 550 °C
IP steam pressure / temperature	28 bar / 540 °C
LP steam pressure / temperature	6.3 bar / 232 °C

3. CONVENTIONAL CONTROL SCHEME

The classical control scheme of CCPPs is shown in Figure 3. The power output of the HRSG is subtracted by the load demand, thus producing the load request to the GTS. This latter is controlled by means of a closed-loop fuel regulation (PI) and a gain scheduling-based open-loop air control aimed at keeping the exhausts temperature at the gas turbine outlet constant. In addition to the fuel and air control, a thermoregulation is used to limit the fuel flow rate when the (estimated) combustion chamber temperature exceeds safety constraints. The flow rate and the temperature of the GTS outlet exhausts may be considered as known disturbances acting on the HRSG.

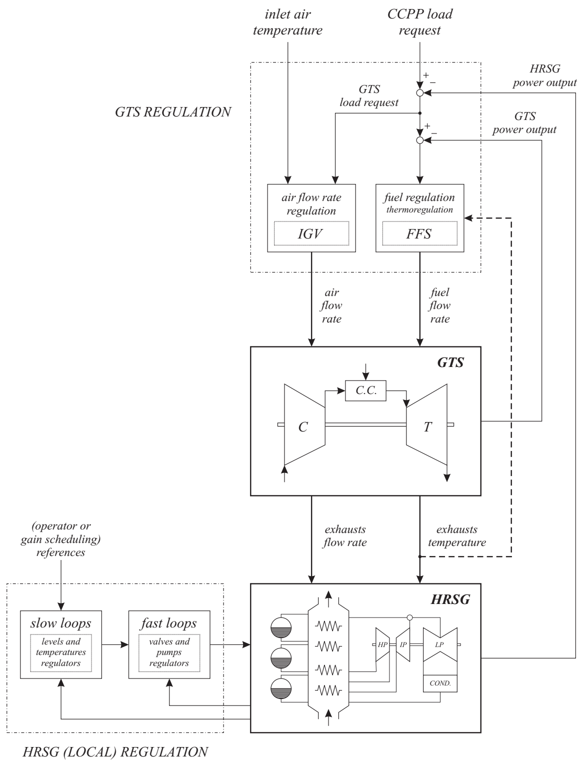

Fig. 3. CCPP conventional control scheme.

The boiler is equipped with local control loops guaranteeing level regulation for the drum boilers and steam temperature control at the SH-2 (superheater) and RH-2 (resuperheater) outlet (desuperheating). These control actions are usually implemented by means of typical two-elements schemes, where the inner “fast” loop directly controls the low level actuator (valve or pump), while the outer “slow” loop ensures the proper regulation of the selected variable. A single-element regulator is applied to the ECO-LP recirculation circuit, in order to keep the water temperature at the economizer inlet constant.

The regulation of the steam temperature at the turbine inlet (HP and IP stages) is performed by desuperheating the corresponding steam fluxes, i.e. by injecting “cold” water upstream the inlet section of the two heat exchangers (SH-2 and RH-2). The spray valves regulation is conventionally performed through decentralized PI-based control loops, implemented in a typical frequency decoupled scheme, as shown in Figure 4

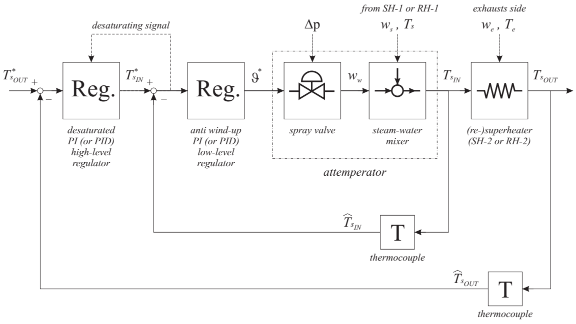

Fig. 4. Two-elements control scheme of the steam temperature.

4. NONLINEAR MODEL PREDICTIVE CONTROL ALGORITHM

The basic nonlinear MPC algorithm proposed in (Magni and Scattolini, 2004) and adopted in the following has been developed for the regulation of a nonlinear model described by

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

where x is the vector of (measurable) states and u is the vector control variables.

Given a sampling period T, letting $t_k = kT$ be the sampling instants, and according to the receding horizon paradigm (Mayne *et al.*, 2000), the adopted method implicitly computes a sampled feedback control law $u(t) = \kappa(x(t_k))$, $t \in [t_k, t_{k+1})$ by minimizing the performance index

$$J = \int_{t_k}^{t_k+N_p} \left\{ \|x(\tau)\|_Q^2 + \|u(\tau)\|_R^2 \right\} d\tau + \|x(t_k+N_p)\|_\Pi^2$$

subject to the following set of constraints:

$$u(t) \in U \quad , \quad x(t) \in X$$
$$x(t_k+N_p) \in X_f$$

In this formulation, N_p is the prediction horizon, Q, R and Π are positive matrices which represent free design parameters, U, X are sets describing physical constraints, while X_f is a further design knob to be properly selected. Usually, X_f is chosen as a positive invariant set of an auxiliary control law guaranteeing local stability. What characterizes this method with respect to other nonlinear MPC algorithms, is the possibility to account explicitly for the hybrid nature of sampled data control systems. In fact, the plant, the state and input constraints and the performance index to be minimized are described in continuous time, while the manipulated variables are allowed to change at fixed and uniformly distributed sampling times. Moreover, it has been shown in (Magni and Scattolini, 2004) that a proper selection of the terminal weight Π and of the terminal set X_f guarantees the exponential stability of the origin.

With respect to the above basic formulation, and in order to apply the algorithm to the case at hand, it has been extended to include the presence of exogenous disturbances and a suitable coordinate transformation has been performed. As for the optimization procedure to be completed at any sampling time, it relies on the *real-time iteration scheme* described in (Diehl *et al.*, 2002). This scheme is based on Bock's direct multiple shooting method (Bock and Plitt, 1984) that reformulates the optimization problem into a suitable finite dimensional nonlinear programming problem (NLP) with a special structure, and solves this NLP with an iterative optimization algorithm.

5. NMPC REGULATION

The NMPC algorithm has been used for control of the plant simulator with a sampling period of 10 s. The prediction horizon has been set to 10 min, which roughly is the value of the settling time associated to the slower temperature dynamics. At any sampling time, the future sequence of piecewise constant control signals has been computed through optimization with the additional constraint that only 6 future control moves are allowed, hence the so called control horizon has been set equal to 1 min. Moreover, constraints have been imposed on the manipulated variables, depending on the structural characteristics of the spray valves. Finally, a normalization of the state, input and output variables has been used to ease the tuning of the free design parameters.

5.1 Scheme A: NMPC of steam temperatures

As proposed in (Aurora *et al.*, 2004), a nonlinear MPC regulator has been used to replace the PI or PID-based high-level controllers of the steam temperatures, with the aim of improving their control performances. According to the commonly adopted MPC design practice, the fast low-level loops have been maintained (see Figure 5). Hence, the nonlinear MPC regulator provides references for the desuperheating water flow rates (manipulated variables) on the basis of the available measurements of the steam temperature at the SH-2 and RH-2 outlet (controlled variables) and of the exhausts temperature and flow rate at the HRSG inlet section (known disturbances).

A number of simulation experiments have been done to assess the performances of the MPC algorithm.

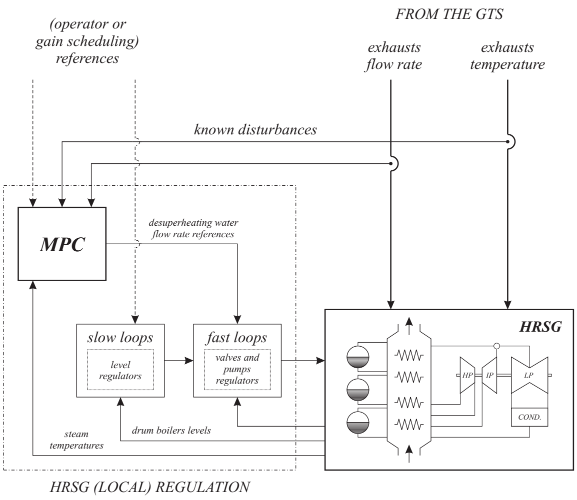

Fig. 5. NMPC of the steam temperatures: scheme of implementation.

Among them, the most significant are those corresponding to load ramp variations. In particular, the load ramp test presented in Figures 6 and 7 highlights the excellent capabilities of the nonlinear MPC algorithm to control the steam temperatures. In fact, it is apparent that the multivariable regulator provides faster responses with limited over and undershoots with respect to the traditional PI regulation scheme. This result is achieved by virtue of a more aggressive use of the control variables, as proved by the opening profiles of the spray valves.

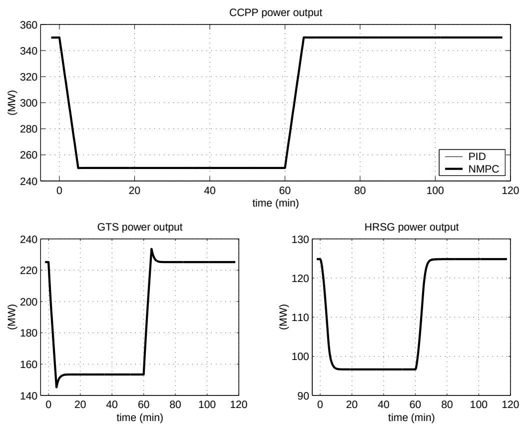

Fig. 6. Load ramp test: CCPP generated load.

It is worth noting that the possibility to improve the performances of the PID scheme are hampered by the difficulty to tune the derivative action, since it easily introduces unwanted sensitivity to measurements noise. On the contrary, the selection of the NMPC parameters is a relatively simple task.

As a drawback, the more aggressive control action performed by the NMPC regulator may produce stronger oscillations of the drum boiler levels. In turn, this effect can be critical when the boiler is provided with natural circulation evaporators, thus suggesting to extend the multivariable control strategy to the drum boiler levels, as discussed in (Astrom and Bell, 2000).

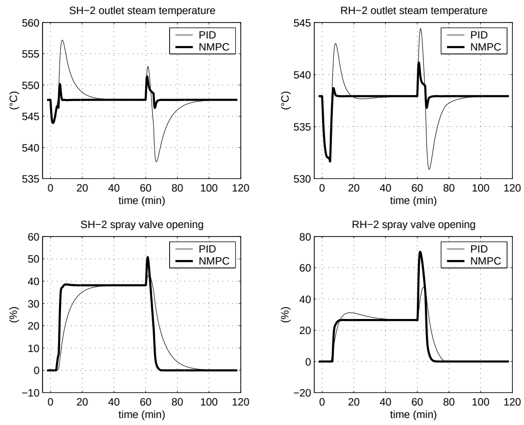

Fig. 7. SH-2 and RH-2 outlet steam temperatures and spray valves opening.

5.2 *Scheme B: NMPC of GTS air flow rate*

As shown in Figure 7, during the first part of the descending load transient, the RH-2 steam temperature control exhibits poor performances - with NMPC as well as with the conventional PI control scheme - because of the saturation of the selected actuators.

The steam temperatures behavior is a direct consequence of the exhaust temperature and flow rate perturbation at the GTS outlet during the falling load ramp. In particular, the conventional GTS control scheme is usually provided with static maps for the air flow rate regulation - function of the load request - with the aim of keeping the exhaust temperature approximately constant at any load (see Figure 3).

In order to improve the steam temperature regulation, NMPC has been also used to compute an additional corrective term to the air flow set-point provided by the static map (see Figure 8). For safety requirements, the conventional exhaust temperature regulation has not been completely replaced with NMPC, and suitable lower and upper bounds have been set for the additive control signal, which vanishes in steady-state. The steam temperatures control performances are strongly improved, as attested by simulations (see Figure 9).

5.3 *Scheme C: NMPC for efficiency optimization*

CCPPs efficiency improvement at partial load is a task of great interest, in the context of their participation to the grid frequency regulation. It can be performed by properly reducing the GTS air flow rate with the load request also at the steady state. Actually, in order to prevent an excessive NOx production, a lower bound must be set for the excess air ratio in steady-state operating conditions.

Encouraging preliminary results have been obtained in simulation. They are shown in Figure 10. The GTS air flow rate reduction operated by NMPC causes an exhaust temperature increase. The resulting HRSG

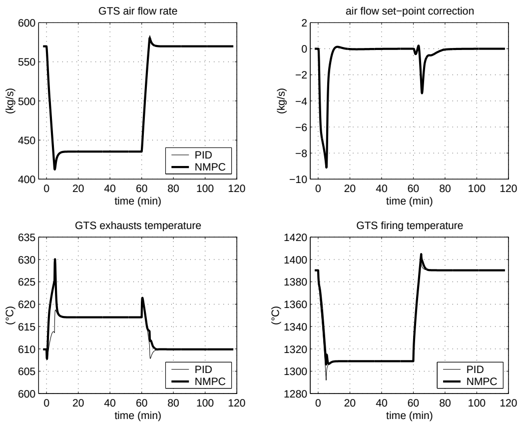

Fig. 8. NMPC of GTS air flow rate and GTS temperatures.

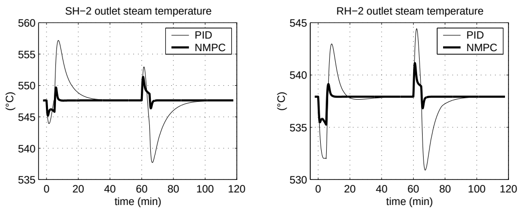

Fig. 9. SH-2 and RH-2 outlet steam temperatures

efficiency improvement allows for a substantial fuel saving at partial load (about 0.3% at 70% base load), with respect to the conventional regulation. At the same time, the steam temperature control exhibits excellent performances, as in the previous case (see Figure 11).

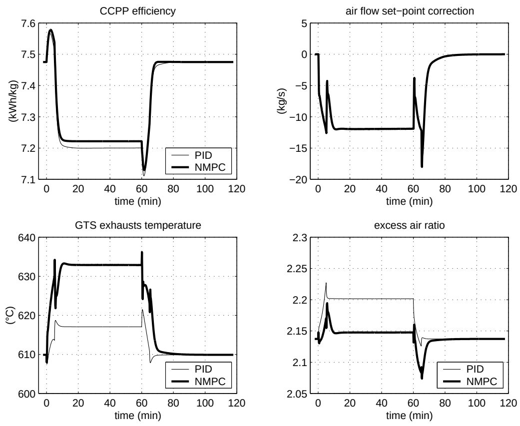

Fig. 10. NMPC of GTS air flow rate for plant efficiency optimization.

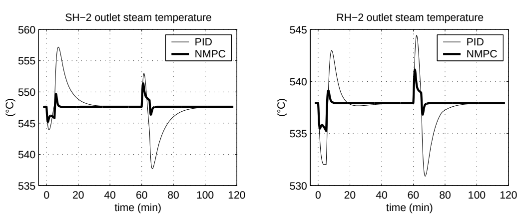

Fig. 11. SH-2 and RH-2 outlet steam temperatures

6. CONCLUSIONS

A simplified, but reliable nonlinear model of CCPPs has been used to analyze the potential benefits caused by the application of nonlinear MPC to HRSG steam temperatures control and plant efficiency optimization. The obtained results stimulate further research to extend the use of MPC to other control loops.

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