15th Triennial World Congress, Barcelona, Spain

MULTIVARIABLE PREDICTIVE CONTROL OF A THERMAL POWER PLANT

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Abstract: This work presents some preliminary results of a project aimed at the application of industrial Model Predictive Control (MPC) to thermal Power Plants. The rationale which motivates this research is the need to improve the efficiency of power plants to cope with the high levels of competitions induced by the liberalization of the energy market. A detailed plant simulator is coupled to an industrial MPC package implementing the Dynamic matrix Control (DMC) MPC algorithm. The reported simulation results witness the potentialities of MPC applied to power plants.

Keywords: power generation, model based control, model predictive control, temperature control, identification.

1. INTRODUCTION

The liberalization of the energy market in western Europe, and in particular in Italy, has dramatically increased the competition among the energy producers. This calls for higher and higher levels of efficiency in the management of the operating units in order to fulfill with a number of requirements. Among them, the most important are: (i) a better selection of the steady state operating conditions according to precisely quantified economic criteria, (ii) the possibility to operate with flexibility over a wide range of load conditions, (iii) more efficient dynamic control strategies explicitly coping with the constraints imposed by technological limits and by environmental restrictions, (iv) more systematic procedures for the definition of the management strategies and for the control design, so as to also guarantee better documentation and transmission of knowledge.

Due to its almost unique features, which fully comply with the requirements previously listed, Model Predictive Control (MPC), see e.g. the survey papers (Morari et al., 1989; Mayne et al., 2000), has extensively been used during the past twenty years mostly in the chemical and the petrochemical industry, where nowadays is unanimously considered as the proper approach to the control design, see (Qin and Badgwell, 1997). In spite of the many similarities between the problems of managing and controlling (petro)-chemical units and the plants for power generation, the application of MPC to power plants has not yet been exploited in depth. Notable exceptions are the works reported in (Prasad et al.

1997, 1998, 2000), where different control structures based on ad-hoc MPC implementations have been considered to control a reduced order nonlinear plant model and in (Lu and Hogg , 1997), where a real-time laboratory simulator has been used in the testing phase. Experimental results concerning the control with a MPC technique of the temperature and the pressure of the steam at the superheater outlet in a large coal-fired power plant have been reported in (Oluwande and Boucher, 1999).

This paper presents some preliminary results of a joint research project of CESI (Centro Elettrotecnico Sperimentale Italiano), University of Pavia and Aspentech, aimed at the development of a detailed feasibility study concerning the application of a widely used commercial package for MPC, to control the pressure and the steam temperatures in thermal power plants. CESI has more of forty years of experience in the simulation and control of electrical energy generation units and, over the years has developed the ALTERLEGO (Castiglioni et al. 1993, Cori et al. 1989) modeling tool for the construction of detailed plant simulators based on physical models. The University of Pavia has a long standing experience in the theory and application of MPC for linear and nonlinear systems, see e.g. (Clarke and Scattolini 1991, De Nicolao et. al, 1996, 1997, 1998, Magni et. al 1999, 2001), while Aspentech has provided to the project DMCplus, one of the most widely used commercial software environments for predictive control. After the preliminary simulation study here reported, the final goal of this research is the testing of the MPC algorithm on an industrial thermal power plant.

2. THE PLANT MODEL AND THE SIMULATION ENVIRONMENT

The plant simulator represents a conventional once-through 320 MW multi-fuel power plant. The model is built with the modeling tool ALTERLEGO, owned by CESI, which is a modular simulation tool based on module libraries including the main plant components and on an efficient numeric solver. All the modules have been tested over the years with real plant data. The main advantage of using ALTERLEGO is that the modeling work can be done configuring data files instead of writing a software application. Moreover, al the numeric problems are managed in a transparent way by a general and reliable solver.

3. THE MPC ALGORITHM

Dynamic Matrix Control (Cutler and Ramaker, 1979) is one of the most popular and widely used MPC algorithms, with hundreds of applications in the process industry, see e.g. Qin and Badgwell (1997) where about 600 industrial applications of DMC were reported. In the software package DMCplus, the plant is described by step response models, which can be identified by specifying the adopted sampling time, the number of step response coefficients, and a regularization factor. The identified models are then used for the tuning and the preliminary testing of the MPC regulator, which is subsequently used in real-time operations. Among the main features of DMCplus, we here recall the following ones:

1. the computation of the optimal steady state working point, according to economic and safety criteria specified by the user, and under constraints on the values of the manipulated and controlled variables;
2. the possibility to explicitly take into account priorities in the constraints fulfillment, by ranking the manipulated and controlled variables and, in case of unfeasibility, by relaxing the “low priority” constraints;
3. the computation of the dynamic control action through the minimization of a quadratic cost function penalizing the future error variables and the future control moves under dynamic constraints;
4. the possibility to specify different modes of operation, such as set-point tracking, funnel reference trajectories, oscillation bands;
5. the use of feed-forward signals and gain scheduling facilities.

4. THE TRADITIONAL CONTROL STRATEGY AND THE MPC APPROACH

The “traditional” regulation implemented in the ALTERLEGO simulator and widely used in many applications is the classical coordinated control scheme schematically depicted in Fig. 1, where at the right-hand side of the dotted vertical line there is the power regulation scheme, not detailed here for simplicity. In Fig. 1 the signals U_3 and U_4 are set to zero and the other signals involved are:

P	Main steam pressure
T_{SH}	Superheater outlet steam temperature
T_{RH}	Reheat steam temperature
α_{RH}	Opening of the spray valve at the reheater
$\%O_2$	Oxygen percentage in the exausts

The meaning of the blocks in Fig. 1 is:

SP-X	Set-point generation for variable X
Reg-X	Feedback regulator of variable X
Req-X	Request generation for variable X

The feedback regulators used in the scheme are mostly PI. Static nonlinear elements and logic switches are also used for performance enhancement and safety requirements. Finally, many loops are implemented according to a cascade structure. In particular, the PI regulator used to control the reheat steam temperature T_{RH} produces the reference signal for the inner loop closed on the reheat attemperator. The same structure, not reported in the figure, is used for the regulation of the superheater outlet steam temperature.

In order to reduce the impact of the introduction of MPC on the plant operators, it has been decided substitute only a limited number of traditional regulation blocks. Specifically, it has been observed that:

1. the transients of the generated power are much faster than the other dynamic phenomena and the power regulation is extremely critical;
2. the regulation of the temperatures (T_{SH} and T_{RH}) is difficult for the heavy couplings between the manipulated and controlled variables;
3. in order to increase the overall efficiency, it is worth maintaining the reheat spray valve as close as possible in static conditions;
4. the use of flow gas recirculation is difficult in standard control schemes, where it is usually generated by a nonlinear feed-forward action. Indeed, it easily induces strong oscillations in all the controlled variables.

For these reasons, the MPC regulator has been used to replace the Pressure and T_{SH} regulators (gray boxes in Fig. 1), and to compute the two additional signals U_3 and U_4 acting on the gas recirculation request and on the reference signal for the reheat attemperator respectively. The goal is to achieve a tighter control action of P, T_{SH} and T_{RH} during dynamic transients caused by load variations and to compute the steady-state values, and in particular the value of α in order to enhance the plant efficiency and the life duration of the plant components.

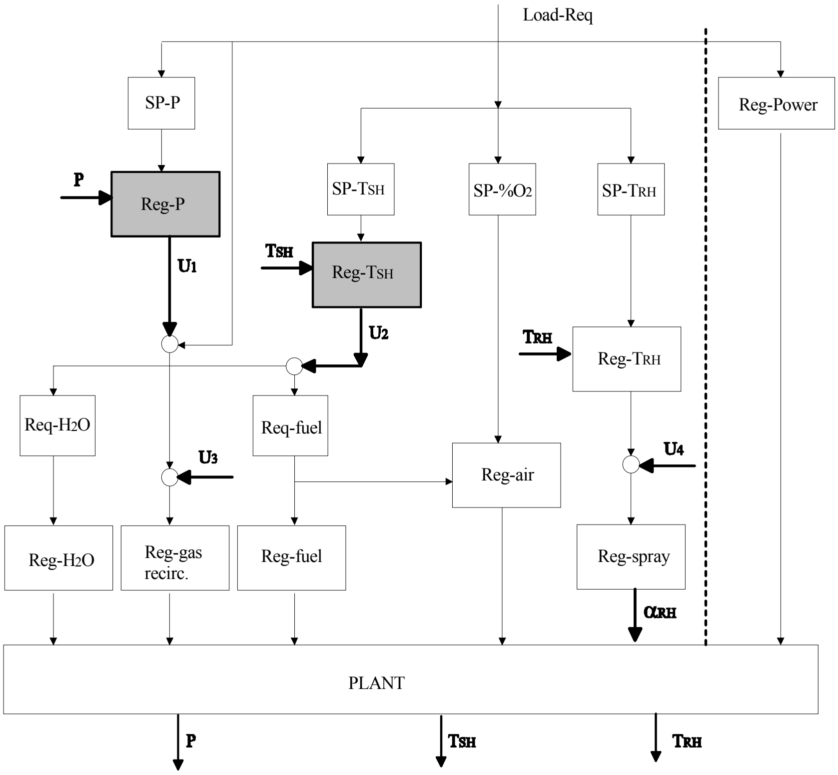

Fig. 1 The coordinated control scheme

5. THE IDENTIFICATION PROCEDURE

The identification procedure has been performed in different steps. First, the PI regulators Reg-P and Reg- T_{SH} in Fig. 1 have been disconnected and step changes have been imposed to the four manipulated variables U_1-U_4. This allowed to have a rough estimate of the dominant time constants of the process and to fix the sampling time for the MPC implementation, which has been set to 1 min. From these responses it has been apparent the presence of inverse responses, which are symptom of a difficult control problem. The information provided by this preliminary phase has also been used to design the PRBS signals used to excite the system in the frequency range of interest. The characteristics of the PRBS have been selected according to the guidelines given in Rivera and Jun (2000). Then, some identification experiments have been performed by exciting one input at a time and by using the identification package of DMCplus for the estimation of the models step responses.

6. THE CONTROL DESIGN AND THE SIMULATION RESULTS

The MPC regulator has been designed according to the following guidelines:

1. the variables P, T_{SH} and T_{RH} have been controlled in tracking mode, that is a fixed reference signal has been forced for anyone of them;
2. the range of variations of the variable α_{RH} has been limited to increase the plant efficiency;
3. the future variations of the controlled variable U_3 have been heavily penalized in order to reduce the oscillations induced by an excessive use of the gas recirculation;
4. under the same values of the other tuning parameters, two different regulators, called in the sequel MPC1 and MPC2, were designed ranking the controlled variables in different ways. Specifically, the ranking adopted in MPC1 is1) α_{RH}, 2) P, 3) T_{SH} and 4) T_{RH}; while MPC2 is derived according to the ranking 1) P, 2) T_{SH} and 3) T_{RH} 4) α_{RH}

Experiment 1

The performed experiment reported in the sequel makes reference to a load variation from 240 MW to 280 MW according to a step profile, which allows one to reach the new operating condition in 4 min. The transients produced by the regulators MPC1 and MPC2 in this load rejection experiment are compared to those provided by the traditional coordinated scheme in Figs. 2-5.

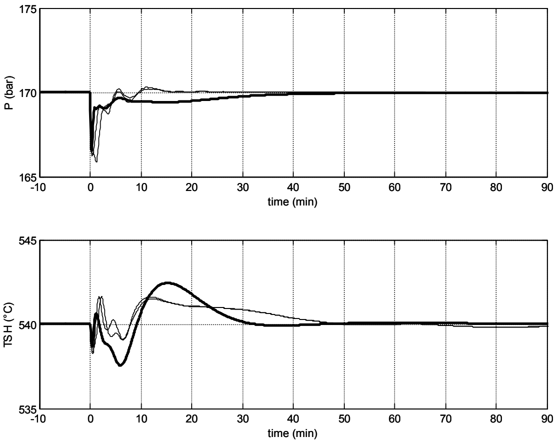

Fig.2: Transients of P and T_{SH} produced by the traditional coordinated control scheme (bold line) and by the regulators MPC1 and MPC2 (thin lines).

From these figures it is apparent that the MPC regulators perform better than the coordinated scheme both in terms of dynamic performance and in steady state conditions. In fact, it is clear that a tighter dynamic control action is performed on the temperatures T_{SH} and T_{RH} , while the control of P is not very different. As for the adopted operating point, note that MPC1 and MPC2 maintain the reheat spray valve at a lower level than the coordinated control does. At the same time, the amount of gas re-circulation flow rate is sensibly smaller with MPC1 and MPC2, see Fig. 5 where the additive signal U_3 in the scheme of Fig. 1 is sensibly negative. This corresponds to a significant improvement in the efficiency of the plant, that is in sensible economical savings. These considerations are also witnessed by the values assumed by the Root Mean Square Errors RMS computed for P, T_{SH} and T_{RH} in the considered temporal window of 90 min, which are

RMS	P	T_{SH}	T_{RH}
Coord.	0.0069 %	0.0064 %	0.0057 %
MPC1	0.0087 %	0.0034 %	0.0025 %
MPC2	0.0067 %	0.0032 %	0.0024 %

Moreover, the mean value of the controlled variable α_{RH} is

	α_{RHmean}
Coord.	12.73 %
MPC1	10.04 %
MPC2	10.23 %

It is remarkable to note that the coordinated control scheme used for comparison is considered to be very well tuned over years of experience.

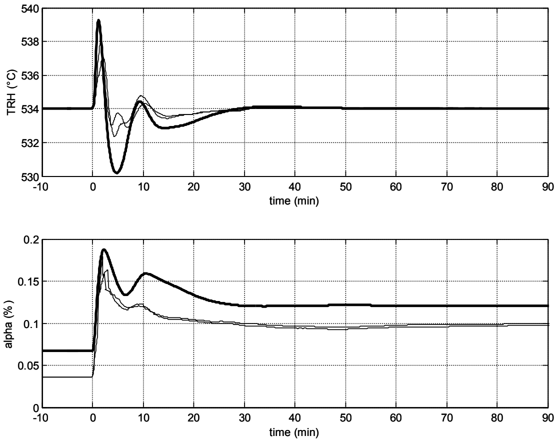

Fig.3: Transients of T_{RH} and α_{RH} produced by the traditional coordinated control scheme (bold line) and by the regulators MPC1 and MPC2 (thin lines).

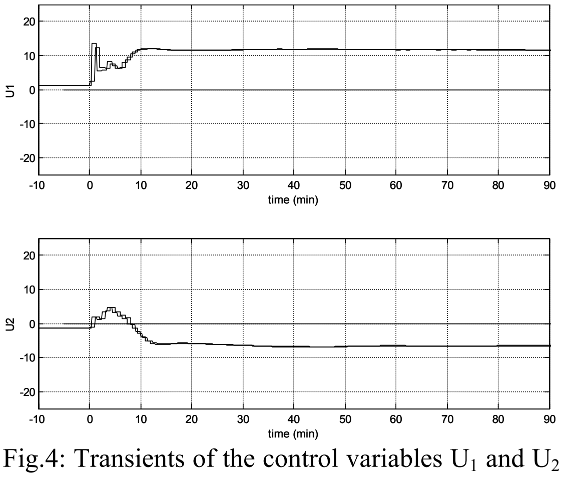

Fig.4: Transients of the control variables U_1 and U_2 produced by the regulators MPC1 and MPC2.

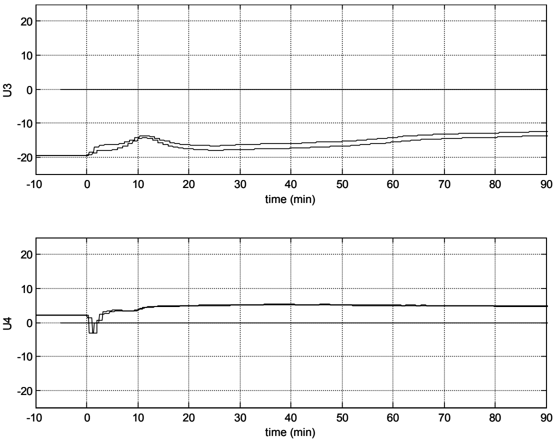

Fig.5: Transients of the control variables U_1 and U_2 produced by the regulators MPC1 and MPC2.

Experiment 2

The MPC2 regulator was compared to the traditional coordinated control scheme by carrying out an high amplitude load variation from 140 MW to 320 MW, according to a ramp profile characterized by a standard load rate of 3.2 MW/min. This test is particularly significant to verify the robustness of the proposed multi-variable controller over a wide range of operating conditions.

Figs. 6-7 show the results of this experiment.

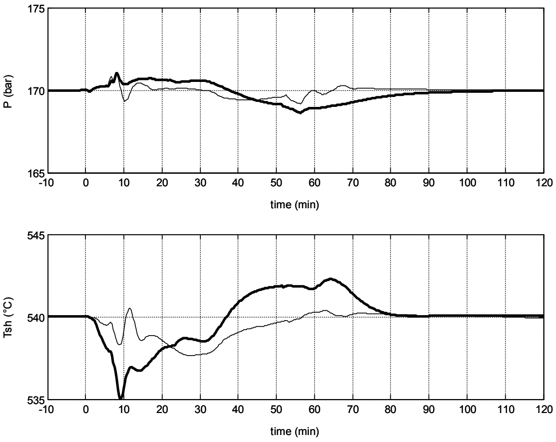

Fig.6: Transients of P and T_{SH} produced by the traditional coordinated control scheme (bold line) and by the regulator MPC2 (thin lines).

Also in this slow-rate test it is possible to see the improved response offered by the MPC regulation, as confirmed by the Root Mean Square Errors RMS, referred to the considered 120 min time window and reported in the following table

RMS	P	T_{SH}	T_{RH}
Coord.	0.3343 %	0.2969 %	0.2455 %
MPC2	0.1726 %	0.1665 %	0.1651 %

Fig. 7 shows that the reheat spray valve is widely used by the MPC2 controller during transients, while its opening is maintained at the lower admissible value in steady-state operations, thanks to an improved recircle regulation, as already remarked about the previous experiment.

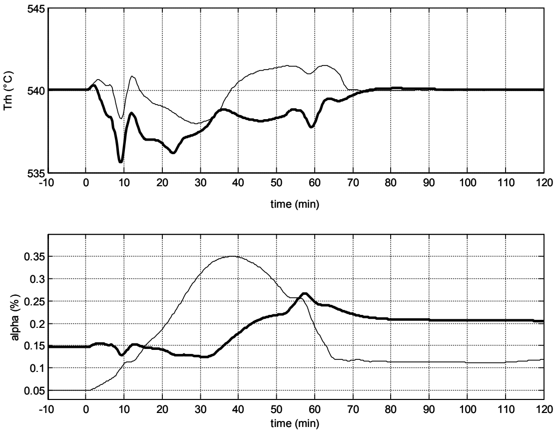

Fig.7: Transients of T_{RH} and α_{RH} produced by the traditional coordinated control scheme (bold line) and by the regulator MPC2 (thin line).

7. BENEFITS FOR INDUSTRIAL APPLICATIONS

The reported research has witnessed the potential economical benefits achieved by the use of MPC to power plants. Specifically, it appears to be possible to achieve two main goals:

1. reduction of the standard deviation on the controlled key-variables up to 50%;
2. reduction of the response times against load variations or disturbances from 30% to 50%.

By acting on these two factors, in the specific case of thermal power plants, it is possible to automatically and safely manage the plant nearer to the operating limits. This means that the rated value of main pressure and temperature of the superheated steam can be increased, with consequent increase in plant efficiency and decrease in consumptions. Moreover, thanks to the time responses reduction, it is possible to considerably increase the flexibility in the management of the production units; in turn, this allows to quickly change the operating conditions and, consequently, to have access to dynamic services.

Both these factors make undoubtedly interesting the evaluation of innovative control projects for this typology of plants.

Preliminary considerations, on the basis of simulation results, make evident that the increase of the standard values of the steam main pressure and of the temperature gives rise to an improvement of specific consumption of about 1.2 Kcal/KWh/°C and 1.3 Kcal/KWh/bar. By assuming an increase of 5°C and 5 bar respectively, an improvement of specific net consumption of 12.5 Kcal/KWh is attained, which corresponds to an economical saving of 300 ML per year for fuel expenses.

8. CONCLUSIONS AND FUTURE WORK

This paper presented some preliminary results of a feasibility study concerning the application of Model Predictive Control to Thermal Power Plants. Although the analysis has to be further exploited in the forthcoming months, it is already possible to draw some encouraging conclusions, such as:

1. the use of MPC can bring substantial benefits in the management of these plants for a couple of reasons. First, it is possible to improve the dynamic response of the controlled variables. In turn, this means that the plant can be brought nearer to the "optimal" operating point. Second, this "optimal" regime can be computed by minimizing an economic criterion which can be frequently modified to cope with changing operating conditions.
2. The use of a detailed plant simulator and of one of the most widely used commercial products for MPC makes this study very realistic in practice, so that experimentation on production units is planned in the near future.

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