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Control and Optimization for Steel Plant Preheating Installations

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Abstract: The paper presents the results of the research performed by the authors on control systems and optimization for the operating process of the heating installations from the blast furnace at a steel plant. This system was developed on two relevant levels interconnected in a hierarchical control structure. The acquisition and control level using specialized microcontrollers was implemented. The supervisory level for the optimization of the combustion process was implemented on an operator console. The solution of the optimization problem represents the optimal decision, translated in real-time procedure to the acquisition and control level.

1. INTRODUCTION

The complexity of the metallurgical installations and the difficulties of planning and technological functioning are well known. Significant improvements for the heating steel plant installations area have been obtained when numerical equipments and modern theory of automatic control were introduced (Taloi, 1993; Avoy, *et al.*, 2002).

In economic and commercial environments, quality and performance are very important criteria. The priorities in this type of processes are productivity, raw materials and the quality of products.

In this context, at ISPAT-SIDEX, an important steel plant in Eastern Europe, a program of modernization was launched in order to feed the plant's blast furnaces with hot air from the heating installations, referred further as cowpers.

The cowper's operating process has three work phases: heating, aeration and cooling. Using efficient synchronization and adequate technological switching, the cowpers are continuously feeding the blast furnace with hot air.

Some particularities of the process can be noticed. The large dimensions of the installation imply a plant model with large delays and distributed parameters, and engaging important flow materials.

The used fuel has many components: methane gas, coke gas and furnace gas, with different caloric powers. A convenient recipe must be calculated to feed the burners.

The quality of the combustion gas and the process nonlinearities introduce important disturbances in exploitation. To evaluate the combustion process, the composition of the residual gas is analyzed; more precisely, the concentrations of O_2 and CO are measured.

The major interest was to improve the cowper's efficiency using an adequate automation solution.

The work has been focused on two main directions:
- design of a data acquisition and control system to maintain the installation in a nominal operating point.
- optimization of the burning process, important consumer of fuel gas.

The conventional control solution, based on analogical systems (Weight and Scrimgeour, 1962), was replaced with numerical control. The numerical solution was computed using the model based - control design procedure, by poles-allocation methods for advanced RST algorithms (Popescu, *et al.*, 2004).

During the identification step RLS methods were introduced using the standard algorithms:

$$\hat{\theta}(k+1) = \hat{\theta}(k) + F(k+1)\phi(k)\varepsilon^0(k+1),\ \forall k \in N$$
$$F(k+1) = F(k) - \frac{F(k)\phi(k)\phi^T(k)F(k)}{1+\phi^T(k)F(k)\phi(k)}$$
$$\varepsilon^0(k+1) = y(k+1) - \hat{\theta}^T(k)\phi(k),\ \forall k \in N \tag{1}$$

with the following initial conditions:

$$F(0) = \frac{1}{\delta}I = (GI)I,\ 0 < \delta < 1 \tag{2}$$

The estimated $\hat{\theta}(k)$ represents the parameters of the polynomial plant model.

In the control design phase, the RST control algorithms were evaluated by poles allocation methods, covering the reference tracking and the disturbances rejection:

$$u(k)=\frac{T(z^{-1})}{S(z^{-1})}r(k)-\frac{R(z^{-1})}{S(z^{-1})}y(k) \qquad (3)$$

Closed-loop poles are the roots of the polynomial $P(z^{-1})=AS+BR$, which define the overall control performances.

The reference tracking is achieved through a reference model $\frac{B_m(z^{-1})}{A_m(z^{-1})}$, which generates the desired trajectory, based on the system reference (Landau, 1995).

Before the implementation stage, the performances of the designed systems have been verified by simulation. The authors had to make some improvements of the nominal control system using adaptive and robust control, to preserve the real-time performances (Landau, 1995). Closed-loop system design was achieved with dedicated software, PIM-PCREG, which performs the identification and model based control design.

At the supervisory level, a mathematical global model has been obtained to describe the combustion process, using LS methods, based on the standard LS algorithm:

$$\hat{z}=f(p,y) \qquad (4)$$

where z is the output data acquisition vector, y is the input data acquisition matrix and $\hat{p}$ is the vector of estimated parameters, with the following expression:

$$p=(y^T y)^{-1} y^T z \qquad (5)$$

An optimization problem was built in restrictive conditions. The oxygen concentration in residual gas was chosen as quality criterion, depending on fuel gas flow y_1 and combustion air flow y_2:

$$\hat{z}(\%O_2)=f(y_1,y_2) \qquad (6)$$

with the following technological constraints:

$$\begin{aligned}
&y_{1L} \le y_1 \le y_{1H}\\
&y_{2L} \le y_2 \le y_{2H}\\
&\hat{z}_{1L} \le \hat{z}_1(y_1,y_2) \le \hat{z}_{1H}\\
&\hat{z}_{2L} \le \hat{z}_2(y_1,y_2) \le \hat{z}_{2H}\\
&\hat{z}_{3L} \le \hat{z}_3(y_1,y_2) \le \hat{z}_{3H}
\end{aligned} \qquad (7)$$

The implicit constraints, evaluated by the same LS identification procedure, are imposed for the functions $\hat{z}_1$ (CO concentration), $\hat{z}_2$ (cowper cupola temperature), $\hat{z}_3$ (flue gases temperature), evaluated as the criterion-function $\hat{z}(\%O_2)$.

The solution (y_1^*, y_2^*) of the optimization problem (4), (6) was obtained using Boxe method and SISCON software package (Popescu, 2005).

This software is written in C++ language, determines the mathematical decision models of the systems (which may be either linear or non-linear) and also solves the global optimization problem. The syntactic analyzer, which reads and interprets the functions, handles almost any type of non-linearity. It gives also the possibility to select the input variables or to automatically generate combinations of input variables in order to find the closest combination to reality. The data can be taken from text files or can be directly entered by using the keyboard. The user can select the optimization method, depending of the specific optimization problem.

2. DATA ACQUISITION AND CONTROL LEVEL DESIGN

The chosen automation solution assures the heating control, and the recipe of fuel gas composition. Twenty-one parameters are measured, and seven of them are controlled (Popescu, *et al.*, 2004).

2.1 Combustion process control

The combustion control provides two separated control systems, one for the fuel flow (FRC-1) and another for combustion air flow (FRC-2) in order to maintain an operating combustion point. The quality of the combustion process is evaluated measuring the quality of residual gases (e.g. concentration of O_2).

Concerning FRC-1, in Fig. 1 is presented the system's time-response. Similar results have been obtained for FRC-2, as it can be seen in Fig. 2.

For FRC-1 the following model has been identified:

$$\begin{aligned}
\hat{B}_1 &= 0.19\, z^{-1}\\
\hat{A}_1 &= 1-0.905\, z^{-1}
\end{aligned} \qquad (8)$$

For FRC-1, the desired performances are given as follows:
- disturbance rejection:

$$P(z^{-1})=1-1.314\, z^{-1}+0.432\, z^{-2} \qquad (9)$$

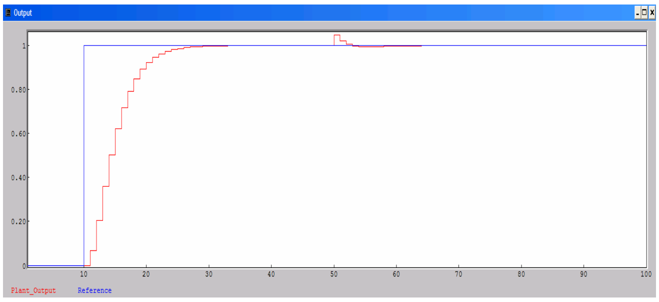

Fig. 1. Reference tracking and disturbance rejection for FRC-1 control system

- reference tracking:

$$\frac{B_m(z^{-1})}{A_m(z^{-1})}=\frac{0.067+0.051\,z^{-1}}{1-1.314\,z^{-1}+0.432\,z^{-2}} \qquad (10)$$

The correspondent numerical RST algorithm has been calculated:

$$\begin{aligned} R_1 &= 0.5907-0.4731\,z^{-1} \\ S_1 &= 0.1903-0.1903\,z^{-1} \\ T_1 &= 1-1.314094\,z^{-1}+0.43171\,z^{-2} \end{aligned} \qquad (11)$$

which assures for the FRC-1 system the time-response presented in Fig. 1.

During the implementation phase, the control algorithm was used in an adaptive version. The model $(\hat{A}_1^k,\hat{B}_1^k)$ is changed to $(\hat{A}_1^{k+1},\hat{B}_1^{k+1})$, and for $(P_1^{k+1}=P_1^k=P_1)$, (R_1^k,S_1^k) is then changed to (R_1^{k+1},S_1^{k+1}), at every sampling period, in order to preserve the real-time performances. The closed-loop identification step has been achieved using the RLS algorithms, where the adaptive error e_1^k was replaced with the adaptive filtered error $e_{1f}^{\ k}$:

$$e_{1f}^{\ k}=\frac{S_1^k}{P_1}(\hat{A}_1^k y_1^k-\hat{B}_1^k u_1^k) \qquad (12)$$

For FRC-2 system a similar model has been identified:

$$\begin{aligned} \hat{B}_2 &= 0.19\,z^{-1} \\ \hat{A}_2 &= 1-0.904\,z^{-1} \end{aligned} \qquad (13)$$

For FRC-2, the desired performances are given as follows:
- disturbance rejection:

$$P(z^{-1})=1-1.314\,z^{-1}+0.432\,z^{-2} \qquad (14)$$

- reference tracking:

$$\frac{B_m(z^{-1})}{A_m(z^{-1})}=\frac{0.067+0.051\,z^{-1}}{1-1.314\,z^{-1}+0.432\,z^{-2}} \qquad (15)$$

The correspondent RST algorithm was:

$$\begin{aligned} R_2 &= 0.455-0.372\,z^{-1} \\ S_2 &= 0.19-0.19\,z^{-1} \\ T_2 &= 1-1.460\,z^{-1}+0.533\,z^{-2} \end{aligned} \qquad (16)$$

The optimal values for the fuel flow and the combustion air flow are calculated at the supervisor level and transferred automatically in the configuration of the two control loops. Therefore is assured an optimal flow ratio for the combustion process.

2.2 *Heating Process Control*

Two control systems are provided, one to control the cold air flow (which must be heated) and the other to control the temperature of hot air entering the furnace.

For FRC-3 (cold air flow control system), the identified model is:

$$\begin{aligned} \hat{B}_3 &= 0.04\,z^{-1} \\ \hat{A}_3 &= 1-0.91\,z^{-1} \end{aligned} \qquad (17)$$

For FRC-3, in terms of performances we have:
- disturbance rejection:

$$P(z^{-1})=1-1.31\,z^{-1}+0.43\,z^{-2} \qquad (18)$$

- reference tracking:

$$\frac{B_m(z^{-1})}{A_m(z^{-1})}=\frac{0.07+0.05\,z^{-1}}{1-1.31\,z^{-1}+0.43\,z^{-2}} \qquad (19)$$

The correspondent RST algorithm was:

$$\begin{aligned} R_3 &= 0.27-0.23\,z^{-1} \\ S_3 &= 0.04-0.04\,z^{-1} \\ T_3 &= 1-1.63\,z^{-1}+0.67\,z^{-2} \end{aligned} \qquad (20)$$

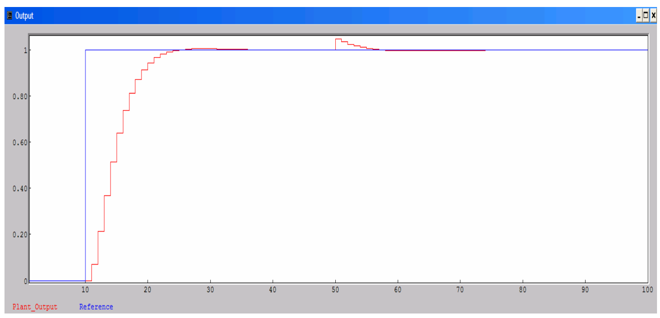

Fig. 2. Reference tracking and disturbance rejection for FRC-3 control system

For hot air temperature control system TRC-4, the following model was identified:

$$\hat{B}_4 = 0.068z^{-1} + 0.052\,z^{-2}$$
$$\hat{A}_4 = 1 - 1.33z^{-1} + 4.49\,z^{-2} \tag{21}$$

The desired performances are given as follows:
- disturbance rejection:

$$P(z^{-1}) = 1 - 0.034\,z^{-1} + 0.004\,z^{-2} \tag{22}$$

- reference tracking:

$$\frac{B_m(z^{-1})}{A_m(z^{-1})} = \frac{0.068 + 0.051\,z^{-1}}{1 - 1.310\,z^{-1} + 0.431\,z^{-2}} \tag{23}$$

and the correspondent algorithm was implemented

$$R_4 = 22.997 - 78.054z^{-1} + 63.135z^{-2}$$
$$S_4 = 1 - 0.268z^{-1} - 0.731z^{-2} \tag{24}$$
$$T_4 = 8.333 - 0.291z^{-1} + 0.037z^{-2}$$

The non-linear components of the system structure imposed a robust implementation of this algorithm. Robust design was based on disturbance-output sensitivity function. For the initial RST controller, detailed above, the sensitivity function is presented in Figure 3.

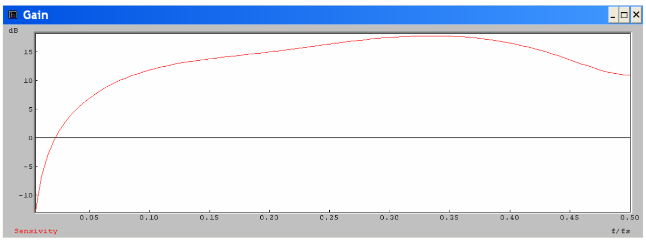

Fig. 3. Sensitivity function for the temperature controller

To assure a specific shaping of the sensitivity function, pre-specified polynomials H_{R4}, H_{S4} were introduced, as follows:

$$H_{S_4} = 1 - 0.320\,z^{-1} + 0.082\,z^{-2} \tag{25}$$

$$H_{R_4} = 1 - 0.068\,z^{-1} + 0.003\,z^{-2} \tag{26}$$

Consequently, the implemented algorithm became:

$$R_4^{'} = R_4 \cdot H_{R4} \tag{27}$$

$$S_4^{'} = S_4 \cdot H_{S4} \tag{28}$$

where H_{R4} and H_{S4} introduce zeros at predetermined frequencies, for convenient adjustment of the sensitivity function (H_{R4} at low frequencies and H_{S4} at band-pass intermediate frequencies).

As a result we obtained an improvement of the system's robustness by 16%.

Finally, the fuel gas flow recipe is assured by systems controlling the ratio between furnace gas flow, methane gas flow and coke flow.

The control systems FRC-5, FRC-6 and FRC-7 respectively have been calculated during the design phase.

The model obtained for FRC-5 was:

$$\hat{B}_5 = 0.038\,z^{-1}$$
$$\hat{A}_5 = 1 - 0.908\,z^{-1} \tag{29}$$

For FRC-5, in terms of performances we have:
- disturbance rejection:

$$P(z^{-1}) = 1 - 1.314\,z^{-1} + 0.432\,z^{-2} \tag{30}$$

- reference tracking:

$$\frac{B_m(z^{-1})}{A_m(z^{-1})} = \frac{0.067 + 0.051\,z^{-1}}{1 - 1.314\,z^{-1} + 0.432\,z^{-2}} \tag{31}$$

The correspondent RST algorithm was:

$$R_5 = 0.27 - 0.234\,z^{-1}$$
$$S_5 = 0.038 - 0.038\,z^{-1} \tag{32}$$
$$T_5 = 1 - 1.635\,z^{-1} + 0.671\,z^{-2}$$

The model and output control for FRC-6:

$$\hat{B}_6 = 0.031\,z^{-1}$$
$$\hat{A}_6 = 1 - 0.905\,z^{-1} \tag{33}$$

For FRC-6, in terms of performances we have:
- disturbance rejection:

$$P(z^{-1}) = 1 - 1.314\,z^{-1} + 0.432\,z^{-2} \tag{34}$$

- reference tracking:

$$\frac{B_m(z^{-1})}{A_m(z^{-1})} = \frac{0.067 + 0.051\,z^{-1}}{1 - 1.314\,z^{-1} + 0.432\,z^{-2}} \tag{35}$$

The RST algorithm obtained was:

$$R_6 = 0.27 - 0.234\,z^{-1}$$
$$S_6 = 0.031 - 0.031\,z^{-1} \tag{36}$$
$$T_6 = 1 - 1.635\,z^{-1} + 0.671\,z^{-2}$$

Finally, for FRC-7 the identified model had the following form:

$$\hat{B}_7 = 0.476 z^{-1}$$
$$\hat{A}_7 = 1 - 0.905 z^{-1} \quad (37)$$

For FRC-7, the specified performances were:
- for disturbance rejection:

$$P(z^{-1}) = 1 - 1.314 z^{-1} + 0.432 z^{-2} \quad (38)$$

- for reference tracking:

$$\frac{B_m(z^{-1})}{A_m(z^{-1})} = \frac{0.067 + 0.051 z^{-1}}{1 - 1.314 z^{-1} + 0.432 z^{-2}} \quad (39)$$

The computed RST numerical algorithm was:

$$R_7 = 0.096 - 0.857 z^{-1}$$
$$S_7 = 0.476 - 0.476 z^{-1} \quad (40)$$
$$T_7 = 1 - 1.809 z^{-1} + 0.819 z^{-2}$$

The hardware implementation for the data acquisition and control level was accomplished on a two 16-bits micro-controllers configuration connected to the process.

3. OPTIMIZATION LEVEL DESIGN

The purpose of the decision level is to optimize the combustion process in restrictive technological conditions (Popescu, *et al.*, 2004; Roberts, 2001).

First of all, a supervisory model (Fig. 4) has been evaluated: $z(\%O_2) = f(y_1, y_2)$. The constraints models: CO concentration ($\hat{z}_1$), cowper cupola temperature ($\hat{z}_2$) and residual gases temperature ($\hat{z}_3$), all of them depending on fuel flow (y_1) and combustion air flow (y_2), were also calculated:

$$\hat{z}_1(\%CO) = f_2(y_1, y_2)$$
$$\hat{z}_2(T_{cowper\,cupola}) = f_3(y_1, y_2) \quad (41)$$
$$\hat{z}_3(T_{flow\,gases}) = f_4(y_1, y_2)$$

All models have been computed using LS experimental identification method (Dauphin-Tanguy, *et al.*, 2004).

The procedure of data acquisition is accomplished during the first interval of cowper's heating phase, on an imposed duration, with an acquisition rate of two seconds and a resolution of 256 observations.

For the usual data set, measured in real-time conditions, the following non-linear models are estimated:

$$\hat{z} = -9.665 + 0.229 y_1 - 0.0009 y_1^2 + 0.0104 y_2$$
$$\hat{z}_1 = 4282.875 - 21.566 y_1 - 0.077 y_1^2 - 21.500 y_2 \quad (42)$$
$$\hat{z}_2 = 1277.613 + 0.001 y_1^2 - 0.387 y_2$$
$$\hat{z}_3 = 499.162 - 0.002 y_1^2 - 3.499 y_2$$

A parametric optimization problem was built, which, for the considered example, is stated as follows:

$$\min_{y_1, y_2} z = -9.665 + 0.229 y_1 - 0.0009 y_1^2 + 0.0104 y_2 \quad (43)$$

with the following restrictions:

$$0 \le \hat{z}_1 \le 450\, ppm$$
$$0 \le \hat{z}_2 \le 1300^o C$$
$$0 \le \hat{z}_3 \le 340^o C \quad (44)$$
$$96.309 \le y_1 \le 102.452$$
$$46.602 \le y_2 \le 57.992$$

The solution is the optimal operating point for the combustion process:

– air combustion flow: $y_1^* = 97.469\ m^3/h$,

– fuel flow: $y_2^* = 47.804\ m^3/h$,

for which it results a minimum value of O_2 concentration in flue gases:

$$z_{\min}(\%O_2) = 4.6\% \quad (45)$$

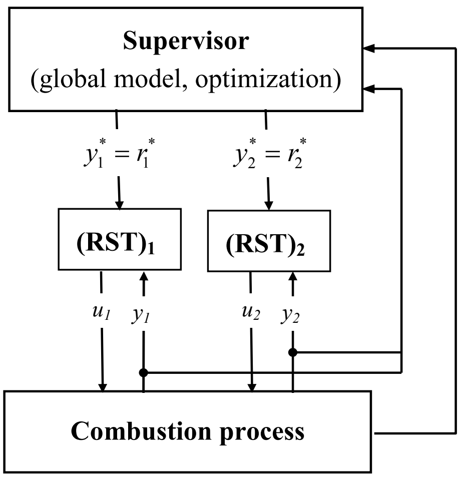

Fig. 4. Supervisory control level

At the same time, corresponding values are obtained for the constraints measures:

$$z_1(\%CO) = 415.73\, ppm$$
$$z_2(T_{cupola}) = 1273.25\, ^oC \quad (46)$$
$$z_3(T_{flue\,gases}) = 311.47\, ^oC$$

The computed optimal point, meaning optimal decision (y_1^*, y_2^*), is automatically transferred as reference $(r_1^* = y_1^*, r_2^* = y_2^*)$ to the inferior control level, which has the task to bring the combustion process at this optimal exploitation point.

The decision level is implemented on the operator console of the numerical equipment.

Analyzing the obtained values there can be noticed a decrease in the concentration of O_2 by 3.15% :

$$I_{O_2} = \left| \frac{4.6 - 4.75}{4.75} \right| \cong 3.15\% \tag{47}$$

which implies a medium reduction in fuel flow by 12.52% :

$$I_{fuel} = \left| \frac{47.804 - 54.649}{54.649} \right| \cong 12.52\% \tag{48}$$

where *54.649* is the mean value for fuel flow, obtained from the experimental data and *47.804* is the optimal value above-mentioned.

Estimating that 57.5% of the fuel flow is represented by methane gas, which implies a medium reduction in methane gas flow by 7.2%, a decrease of $350\, m^3/h$ will be achieved in the demand for methane gas. Taking into account its price, at about 135$ for $1000\, m^3/h$, it results a saving of $47\,\$/h$, which would lead to approximately $340000\ \$/year$ savings.

4. CONCLUSIONS

This paper presents a numerical control and optimization solution for air preheating installations (cowper), implemented at a steel plant in Romania - ISPAT-SIDEX Galati, on the blast furnace no. 5.

The system was designed as a hierarchical structure, organized on two interconnected levels: data acquisition and control level and, respectively, supervisory level.

For the first level, the design methodology uses software resources, based on experimental identification techniques and on pole-allocation methods to compute the control algorithms. Furthermore, in order to improve the control systems performances, adaptive and robust mechanisms were used during the implementation phase.

The second hierarchical level evaluates the optimal decision for the combustion process, solving a parametric optimization problem.

The whole system is implemented as a real time industrial application.

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