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CONTROL AND OPTIMIZATION FOR THE COWPERS OF A STEELMAKING PLANT

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***Abstract**: The paper presents the research results performed by the authors on control systems and optimization for the operating process of the cowpers from the ISPAT-SIDEX 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.*

***Keywords**: MMM processes, identification and control techniques, optimization, real-time control.*

1. INTRODUCTION

The complexity of the metallurgical installations and the difficulties of planning and technological functioning are well-known. Significant improvements in MMM 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 MMM 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 cowpers ensemble.

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 flue gas is analyzed; more precisely, the concentration of O_2 and CO is measured and computed.

Our 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 old conventional control solution, based on analogical systems (Weight and Scrimgeour, 1962), was replaced with numerical control. The numerical solution was conceived using the model based - control design procedure, by poles-allocation methods for PID algorithms (Popescu *et al.*, 1989).

During the identification step, LSR methods were introduced, using the standard algorithms:

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

$$F(k+1) = F(k) - \frac{F(k)\phi(k)\phi^T(k)F(k)}{1+\phi^T(k)F(k)\phi(k)}, \forall k \in N \quad (1)$$

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

with the following initial conditions:

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

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:

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

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:

$$\hat{p} = (x^T x)^{-1} x^T z \quad (4)$$

where $\hat{p}$ is the vector of estimated parameters, x is the input data acquisition matrix, and z is the output data acquisition vector.

An optimization problem was built in restrictive conditions. The oxygen concentration in flue gas was chosen as quality criterion, depending of fuel gas flow x_1 and combustion air flow x_2:

$$\hat{z}(\%O_2) = f(x_1, x_2) \quad (5)$$

with the following technological constraints:

$$\begin{aligned} x_{1L} &\le x_1 \le x_{1H} \\ x_{2L} &\le x_2 \le x_{2H} \\ \hat{z}_{1L} &\le \hat{z}_1(x_1, x_2) \le \hat{z}_{1H} \\ \hat{z}_{2L} &\le \hat{z}_2(x_1, x_2) \le \hat{z}_{2H} \\ \hat{z}_{3L} &\le \hat{z}_3(x_1, x_2) \le \hat{z}_{3H} \end{aligned} \quad (6)$$

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

The solution (x_1^*, x_2^*) of the optimization problem (3), (4) was obtained using Boxe method and SISCON software package (Popescu and Serbanescu, 2001)

This software is written in C++ language, solves the global optimization problem and determines also the mathematical decision models of the systems. These may be linear or non-linear ones. 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. 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 and Fanea, 2001; Popescu *et. al.*, 2000).

2.1. *Combustion process control*

The combustion control provides two separated control systems, one for the fuel flow (FRC-1) and the other 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 flue gases (%O_2, %CO).

Considering the importance of FRC-1 and FRC-2, time-response graphics and control module for these two systems will be presented.

For FRC-1 the following model has been identified:

$$\hat{B}_1 = 0.19033\, z^{-1} \qquad (7)$$

$$\hat{A}_1 = 1 - 0.90484\, z^{-1}$$

The correspondent numerical RST algorithm has been calculated:

$$R_1 = 0.0956 - 0.856\, z^{-1}$$
$$S_1 = 0.4758 - 0.4758\, z^{-1} \qquad (8)$$
$$T_1 = 1 - 1.809\, z^{-1} + 0.819\, z^{-2}$$

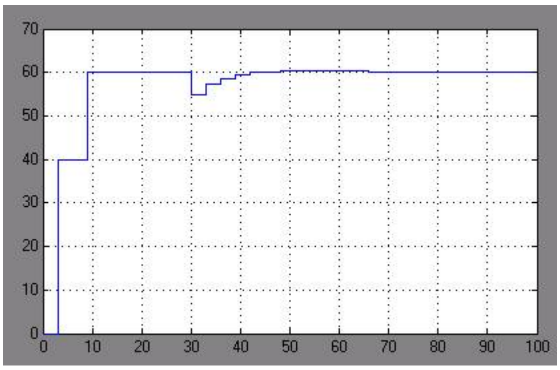

Fig. 1. - FRC-1 - Reference tracking and disturbance rejection.

During the implementation phase, the control algorithm was used in an adaptive version, as follows:

$$(\hat{A}_1^k, \hat{B}_1^k) \rightarrow (\hat{A}_1^{k+1}, \hat{B}_1^{k+1}) \qquad (9)$$

$$(R_1^k, S_1^k) \rightarrow (R_1^{k+1}, S_1^{k+1}) \qquad (10)$$

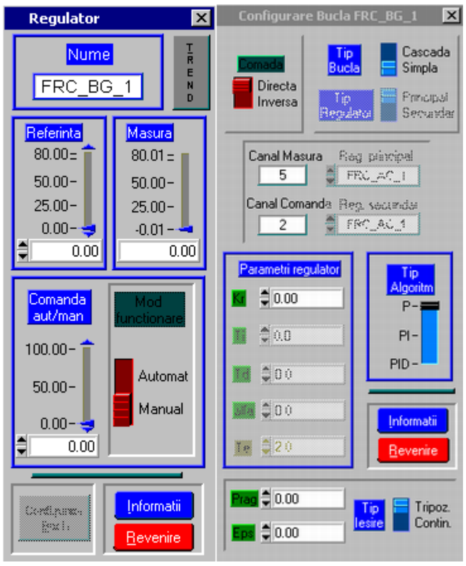

Fig. 2. - FRC-1 – Control module.

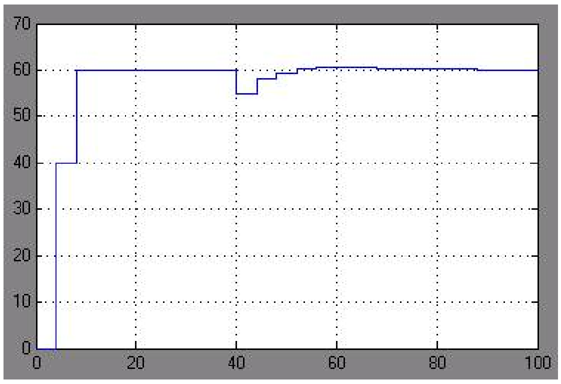

Fig. 3. - FRC-2 - Reference tracking and disturbance rejection.

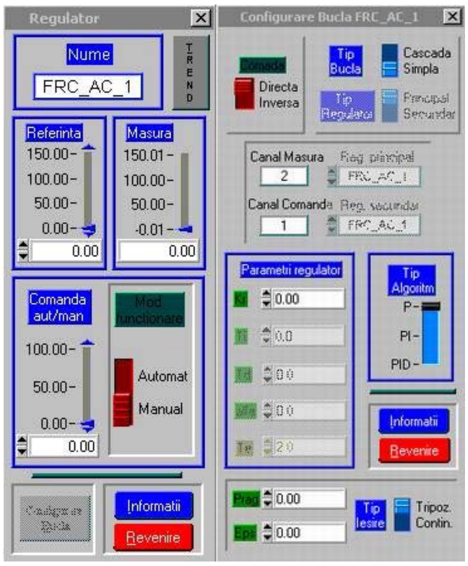

Fig. 4. - FRC-2 – Control module.

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

$$\hat{B}_2 = 0.1903\, z^{-1} \quad (11)$$

$$\hat{A}_2 = 1 - 0.904\, z^{-1}$$

The correspondent RST algorithm was,

$$R_2 = 0.5907 - 0.4731\, z^{-1}$$

$$S_2 = 0.1903 - 0.1903\, z^{-1} \quad (12)$$

$$T_2 = 1 - 1.314094\, z^{-1} + 0.43171\, z^{-2}$$

The optimal values for the fuel flow and the combustion airflow are calculated at the supervisor level and transferred automatically in the configuration of the two control loops. Hereby 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 the hot air exiting the cowper.

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

$$\hat{B}_3 = 0.06777 z^{-1} + 0.05188\, z^{-2} \quad (13)$$

$$\hat{A}_3 = 1 - 1.3299 z^{-1} + 4.49258\, z^{-2}$$

and the RST algorithm was implemented:

$$R_3 = 8.35702 - 11.111503\, z^{-1} + 3.754475\, z^{-2}$$

$$S_3 = 1 - 0.5663\, z^{-1} - 0.4336 z^{-2} \quad (14)$$

$$T_3 = 8.35702 - 11.111503\, z^{-1} + 3.754475\, z^{-2}$$

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

$$\hat{B}_4 = 0.00123 + 0.000139 z^{-1} \quad (15)$$

$$\hat{A}_4 = 1\text{-}1.37198 z^{-1} + 0.37623 z^{-2}$$

and the correspondent algorithm was implemented:

$$R_4 = 1.76889 - 2.03422\, z^{-1} + 0.51875\, z^{-2}$$

$$S_4 = 0.00123 + 0.000605\, z^{-1} - 0.001643\, z^{-2} \quad (16)$$

$$T4 = 1 - 0.99317 z^{-1} + 0.24660 z^{-2}$$

The non-linear components of the system structure imposed a robust implementation of this algorithm. Robust design was based on sensitivity function, disturbance-output. To assure a specific shaping of the sensitivity function, pre-specified polynomials H_{R4}, H_{S4} were introduced.

Consequently, the implemented algorithm became:

$$R_4 = R_4 \cdot H_{R4}, \quad (17)$$

$$S_4 = S_4 \cdot H_{S4} \quad (18)$$

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. For the most important control system, FRC-6, time response and control module are presented.

The model and output control for FRC-5:

$$\hat{B}_5 = 0.03807 z^{-1} \quad (19)$$

$$\hat{A}_5 = 1 - 0.9084 z^{-1}$$

$$R_5 = 0.27 - 0.23387\ z^{-1}$$

$$S_5 = 0.038065 - 0.038065\, z^{-1} \quad (20)$$

$$T_5 = 1 - 1.63476\, z^{-1} + 0.67099\, z^{-2}$$

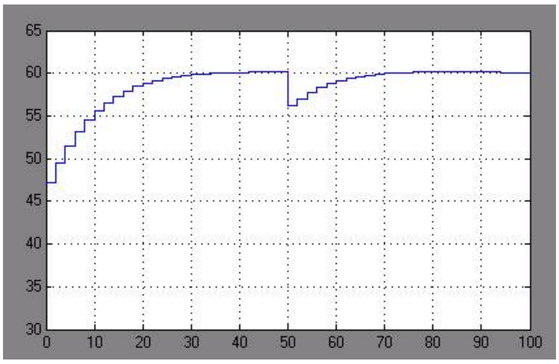

Fig. 5. - FRC-6 - Reference tracking and disturbance rejection.

The model and output control for FRC-6:

$$\hat{B}_6 = 0.0314 z^{-1} \quad (21)$$

$$\hat{A}_6 = 1 - 0.90484 z^{-1}$$

$$R_6 = 0.27 - 0.233846\ z^{-1}$$

$$S_6 = 0.0314 - 0.0314 z^{-1} \quad (22)$$

$$T_6 = 1 - 1.63476\, z^{-1} + 0.670991\, z^{-2}$$

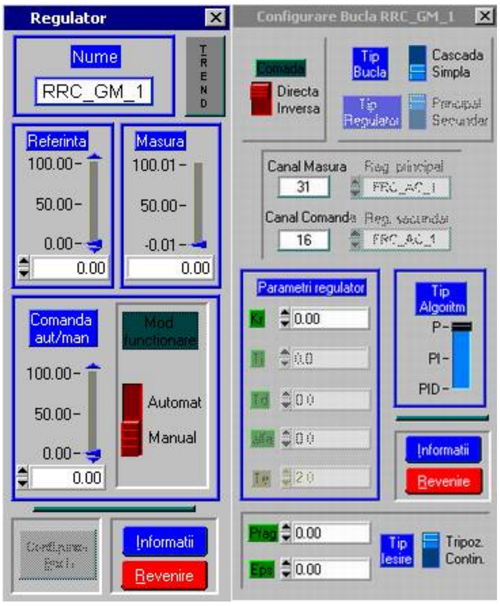

Fig. 6. - FRC-6 – Control module

Finally, for FRC-7:

$$\hat{B}_7 = 0.47581 z^{-1}$$

$$\hat{A}_7 = 1 - 0.90484 z^{-1}$$

$$R_7 = 0.095682 - 0.85697\ z^{-1}$$
$$S_7 = 0.475813 - 0.475813 z^{-1} \quad (24)$$
$$T_7 = 1 - 1.809155 z^{-1} + 0.819142 z^{-2}$$

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 (Wismer, 1972; Roberts, 2001).

First of all, a supervisory model $z(\%O_2) = f(x_1, x_2)$ has been evaluated, and after that, the constraints models: CO concentration $\hat{z}_1$, cowper cupola temperature $\hat{z}_2$ and flue gases temperature $\hat{z}_3$ depending on fuel flow x_1 and combustion air flow x_2 were calculated:

$$\hat{z}_1(\%CO) = f_2(x_1, x_2)$$

$$\hat{z}_2(T_{cowper\ cupola}) = f_3(x_1, x_2) \quad (25)$$

$$\hat{z}_3(T_{flow\ gases}) = f_4(x_1, x_2)$$

These models have been computed using LS experimental identification method (Popescu, 1989).

The procedure of data acquisition is accomplished during the first interval of cowper heating phase, on an imposed duration, with an acquisition rate of 2 seconds and a resolution of 256 observations.

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

$$\hat{z} = -9.665 + 0.229\, x_1 - 0.0009\, x_1^{\ 2} + 0.010\, x_2$$
$$\hat{z}_1 = 4282.875 - 21.566\, x_1 - 0.077\, x_1^{\ 2} - 21.500\, x_2$$
$$\hat{z}_2 = 1277.613 + 0.001\, x_1^{\ 2} - 0.387\, x_2 \quad (26)$$
$$\hat{z}_3 = 499.161926 - 0.002147\, x_1^{\ 2} - 3.49945\, x_2$$

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

$$\min(23)\ \hat{z} = -9.665 + 0.229 x_1 - 0.0009 x_1^{\ 2} + 0.010 x_2 \quad (27)$$

with the following restrictions:

$$0 \le \hat{z}_1 \le 450\ ppm$$
$$0 \le \hat{z}_2 \le 1300^o C$$
$$0 \le \hat{z}_3 \le 340^o C \quad (28)$$
$$96.309 \le x_1 \le 102.452$$
$$46.602 \le x_2 \le 57.992$$

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

$x_1^* = 97469.85$ m^3/h –air combustion flow

$x_2^* = 47804.16$ m^3/h – fuel flow

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

$$z_{\min}(\%O_2) = 4.65\% \quad (29)$$

Using the paper's approach, the fuel gas consumption was reduced by 7.2%.

At the same time, corresponding values are obtained for

$$z_1(\%CO) = 415.73\, ppm$$
$$z_2(T_{cupola}) = 1273.25^o C \quad (30)$$
$$z_3(T_{flue\ gases}) = 311.47^o C.$$

The computed optimal point, meaning optimal decision (x_1^*, x_2^*), is automatically transferred as reference $(r_1^* = x_1^*, r_2^* = x_2^*)$ to the inferior control level, which has the task to bring the combustion process in this optimal exploitation point.

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

4. CONCLUSIONS

This paper presents a numerical control and optimization solution for air heating installations (cowpers) in a steel plant in Romania.

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

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.

To improve 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 system is implemented as a real time industrial application, on the blast furnace no. 5 in ISPAT-SIDEX Galati.

The full results of our project implemented at ISPAT-SIDEX Galati will be presented in the extended paper.

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